

A Battery-Less RFID-Enabled Capacitive Pressure Sensor Integrated in Textile Fabrics

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Abstract—This work presents a battery-less UHF RFID-enabled capacitive pressure sensor based on a multi-layer stacked capacitor (MLSC) architecture, where standard denim acts as a porous and compressible dielectric. An optimized four-layer denim-copper stack produces a nonlinear electromechanical response across the investigated pressure range of 0–4.4 kPa. The measured sensitivity decreases progressively with pressure, from 0.3 pF/kPa at low load to 0.163 pF/kPa at the upper end of the range, with an average sensitivity of 0.19 pF/kPa. Integrated with the capacitive sensing front-end of an EM4152 RFID chip and a conjugate-matched T-match dipole tag, the sensor achieves an empirical limit of detection of 833 Pa. Wireless characterization confirms reliable real-time capacitance monitoring and a maximum read range of approximately 13 m within the ETSI UHF band (865–868 MHz). The proposed platform demonstrates the feasibility of maintenance-free textile-integrated wireless pressure sensing for unobtrusive monitoring scenarios.

Index Terms—Capacitive pressure sensor, textile sensor, flexible electronics, multi-layer stacked capacitor (MLSC), battery-less RFID, T-match dipole antenna.

I. INTRODUCTION

THE advancement of the Internet of Things (IoT) towards pervasive wearable computing is currently impeded by a critical sustainability barrier: energy autonomy. While wearable pressure sensors are pivotal for healthcare diagnostics, gait analysis, and human-machine interaction, conventional active sensor nodes rely heavily on onboard batteries and wired connections [1]. These power sources not only increase the device's bulk and rigidity but also necessitate periodic recharging or replacement, thereby hindering the deployment of truly maintenance-free smart garments designed for “install and forget” applications. Consequently, the development of battery-less, wirelessly interrogated sensing platforms ([2], [3]) has become a primary research imperative.

Passive UHF RFID technology has emerged as a leading enabler for batteryless sensing platforms, leveraging backscatter modulation to transmit data using harvested radiofrequency (RF) energy [4], [5]. Recent wireless and RF-based pressure sensors, including RFID-enabled platforms, often integrate flexible elastomeric dielectrics such as PDMS, Ecoflex, or micro-structured rubber films [6], [7], [8], [9] and textile fabrics [10].

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Conventional passive UHF RFID sensing typically relies on antenna-based methods [2], [11], where variations in the physical parameter of interest (e.g., moisture, strain) induce impedance mismatches that are detected via changes in the Received Signal Strength Indicator (RSSI) [12], backscattered phase, resonance frequency shifts [13] or self-matching mechanisms [3]. While these approaches allow for ubiquitous sensing, they inherently couple the sensing mechanism with the communication link. Consequently, optimizing for high sensitivity often degrades the antenna's radiative efficiency, leading to a trade-off between the sensor's resolution and its read range.

To overcome this limitation, recent architectures utilize sensor-enabled RFID ICs, such as the EM4152 IC [14], which feature dedicated analog front-ends for capacitive or resistive sensing [15], [16]. This approach effectively decouples the sensing element from the antenna design. Therefore, the communication range can be maximized independently of the sensor's dynamic range, ensuring robust performance even in challenging environments [16].

Leveraging this decoupled architecture, this work proposes a first proof-of-concept toward a textile-based battery-less pressure sensor. The presented device consists of a fully passive, battery-free capacitive pressure sensor based on a Multi-Layer Stacked Capacitor (MLSC) architecture [17]. This design leverages the inherent porosity and structural resilience of standard denim fabric as a compressible dielectric. By stacking multiple textile-conductor layers, the proposed MLSC configuration provides a measurable dynamic range of the capacitance change under load, enabling high-sensitivity tactile monitoring while maintaining the fabric's intrinsic breathability. The sensor is integrated with an EM4152 IC [14] containing an analog sensor interface, allowing for direct, battery-less data transmission compatible with standard UHF RFID readers.

This work presents the following contributions:

- a high sensitivity and long range (13 meters) RFID pressure sensor.
- a novel MLSC design integrating denim fabric as a dielectric, and enabling low-cost light pressure sensing.
- a complete electromechanical model of the MLSC sensor and its experimental validation.
- the evaluation of the sensor performance and the validation of the proposed RFID-based sensing system using a Commercial Off-The-Shelf RFID reader over a set of light weights.

TABLE I
MLSC GEOMETRICAL PARAMETERS (IN MM)

$L1$	$L2$	$L3$	H	h	$W1$
15	13	6.5	12	3	15

- a comparison to the current state of the art on UHF RFID-based pressure sensors.

The remainder of this paper is organized as follows. Section II introduces the RFID-based sensor tag architecture and the decoupled sensing principle. Section III presents the design, modeling, fabrication, and electrical characterization of the textile-integrated MLSC capacitive sensor. Section IV describes the T-match dipole antenna design for the RFID IC. Section V validates the complete wireless sensing platform through read-range measurements, real-time sensing experiments, and calibration under controlled loading. Section VI analyzes the key performance metrics, including sensitivity, limit of detection, repeatability, hysteresis, and comparison with the state of the art. Section VII discusses the main limitations of the current prototype and future research directions. Finally, Section VIII concludes the paper.

II. RFID-BASED SENSOR TAG

Unlike conventional antenna-based sensors that infer variations in the target magnitude from subtle signal variations, this system utilizes the dedicated analog front-end within the EM4152 chip to directly convert the captured physical pressure into a precise capacitance value locally, which is then broadcast wirelessly as a pure digital payload. The pure digital readout ensures that the data remains immune to fluctuations in the RF channel quality.

Because the system no longer needs to deliberately alter the antenna's impedance to "perceive" external changes, the tag antenna can be specifically optimized to an ideal conjugate match, achieving the most efficient power transfer. This specific design choice allows the device to independently maximize its communication range while simultaneously maintaining its capacity for high-sensitivity dynamic pressure capture.

III. TEXTILE-INTEGRATED CAPACITIVE SENSOR

This section describes the multi-layer stacked capacitor design mounted on a set of fabric-based dielectric layers and also provides the electromechanical analysis, the presentation of a fabricated prototype and the characterization of the sensor response.

A. MLSC Design

The proposed sensor design consists of a 4-layer MLSC. The stacked structure is used to amplify the effect of denim as a compressible porous dielectric. The sensor geometry is illustrated in Fig. 1. It was designed to provide a tunable capacitance range within the EM4152 IC measurement range ($\Delta C_{IC} = 0 - 17$ pF) over the targeted pressure range of 0-4.4 kPa. The values of the geometrical parameters are provided in Table I.

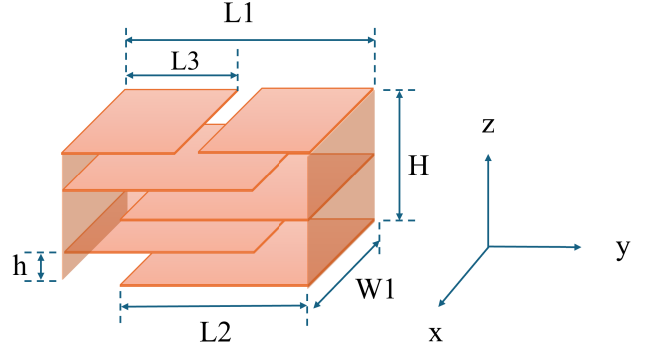


Fig. 1. 3D view and geometrical parameters of the sensor design.

B. Electrical Model

The fundamental principle of the proposed pressure sensor relies on the modification of the geometry and dielectric properties of a parallel-plate capacitor under mechanical load. A simplified model of the MLSC capacitance is:

$$C(h, N) = \sum_{n=1}^N \epsilon_0 \epsilon_M(h) \frac{A}{h} + C_{cal} \quad (1)$$

where ϵ_0 is the vacuum permittivity, $\epsilon_M(h)$ is the effective relative permittivity of the porous dielectric mixture (M), A is the overlap area of the electrodes and C_{cal} is term obtained through calibration to include the effects of interconnections, unmodeled capacitive effects inside the MLSC structure (e.g. coplanar plates) and IC manufacturing offset.

When normal pressure is applied, the dielectric thickness h decreases and the fiber-air mixture densifies. Both effects increase capacitance through reduced plate separation and increased $\epsilon_M(h)$ of the porous dielectric.

The second effect can be described using mixing rules [18]. In fact, porous textile substrates can be modeled as two-phase dielectric mixtures composed of fibers (F) and pores (P). The relative permittivity of the mixture is described using a power law [19], [20]

$$\epsilon_M^\beta(h) = f_F(h) \epsilon_F^\beta + f_P(h) \epsilon_P^\beta \quad (2)$$

where ϵ_F and ϵ_P denote the relative permittivity of the fibers and pores, respectively, $f_F(h)$ and $f_P(h)$ are the corresponding volume fractions. The exponent β is treated as an empirical fitting parameter that captures the microstructural evolution of the porous textile under compression. The material behavior is approximated by a progressive air-fiber volume redistribution where the constraint $f_F(h) + f_P(h) = 1$ is satisfied by construction.

C. Analytical Model for Compression of Fabrics Under Applied Normal Stress

The mechanical response of the denim stack is modeled as a nonlinear compressible medium. Unlike ideal Hookean solids, porous textile materials such as denim exhibit progressive densification under load, leading to an increase in effective stiffness with compression [21], [22], [23]. This behavior

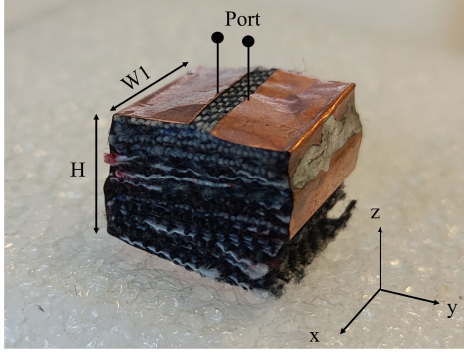


Fig. 2. Fabricated MLSC prototype.

can be interpreted as a strain-dependent effective Young's modulus.

When an external mass m is applied to the sensor, it generates a normal force $F = mg$, g being the gravitational acceleration, which is distributed over the effective contact area A . Instead of assuming linear elasticity, the compressive response is described using a second-order hardening model [23], [24]:

$$F = kx + \alpha x^2 \quad (3)$$

where x denotes the total compression of the multi-layer structure, k is the small-signal stiffness, and $\alpha > 0$ is a hardening coefficient accounting for the progressive densification of the porous textile. This formulation captures the reduction in incremental deformation observed at higher loads.

By substituting $F = mg$ into (3), the compression as a function of applied mass is obtained as:

$$x(m) = \frac{-k + \sqrt{k^2 + 4\alpha mg}}{2\alpha} \quad (4)$$

It should be noted that the model parameters (k , α) are phenomenological and describe the effective response of the complete sensor structure rather than intrinsic material properties of denim alone. These parameters must be identified through experimental calibration of the fabricated device.

The previous expression predicts a monotonic increase in compression with mass, while the incremental sensitivity dx/dm decreases as m increases, in agreement with the experimentally observed behavior.

Assuming uniform deformation across the N stacked dielectric layers, the compression per layer is given by $\Delta h(m) = x(m)/N$. Therefore, the capacitance of the multi-layer structure can be expressed as:

$$C(h, N, m) = \frac{N\epsilon_0\epsilon_M(h)A}{h - \frac{x(m)}{N}} + C_{\text{cal}} \quad (5)$$

D. Sensor Implementation and Electrical Characterization

The MLSC prototype was fabricated in the laboratory using adhesive copper tape mounted on stacked layers of denim fabric ($\epsilon_M = 1.7$) [25]. An image of one prototype is provided in Fig. 2. The fabricated sensor was characterized

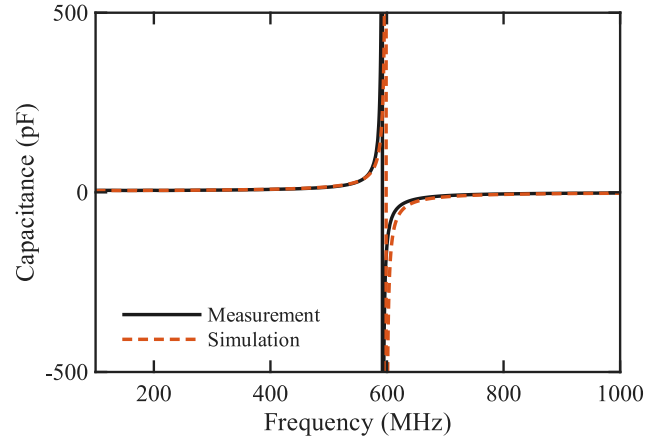


Fig. 3. Comparison between simulation and measurements of sensor capacitance in the unloaded state.

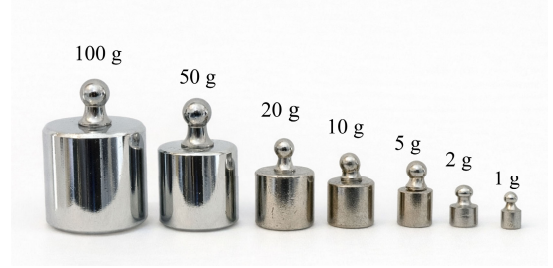


Fig. 4. Set of precision weights used in the experiments.

using a Vector Network Analyzer (VNA). The sensor measurements are compared to electromagnetic simulations using FEKO [26].

Fig. 3 compares the sensor simulated and measured in the unloaded state. The measured results show strong agreement with the simulation across the frequency band, both of which exhibit stable, quasi-static capacitive behavior.

Next, the sensor response is characterized under practical light-touch pressures using a precision weight set (Fig. 4). Discrete masses were applied incrementally at the center of the sensing area to produce a controlled normal load. The applied mass spanned from the unloaded state (0 g) to 100 g. The corresponding nominal pressure was computed as $P = \frac{mg \cdot 10^{-3}}{A}$. Over this range, the pressure spans approximately 0 to 4.4 kPa.

The sensor equivalent capacitance was independently characterized using a VNA. Fig. 5 shows the broadband response under each load. Fig. 6 shows the capacitance measurements extracted at the frequency of 100, 200, 300 and 400 MHz. At low frequencies (e.g. 100 MHz), the dielectric response of the compressible textile stack is stable and the extracted capacitance provides a consistent electrical measure of compression induced changes.

This VNA-based characterization serves as an electrical sanity check of monotonicity and dynamic range compatibility for subsequent RFID measurements. The observed total capacitance swing ($\Delta C \approx 2$ pF @100 MHz) lies within the nominal input range of the capacitive interface of the IC.

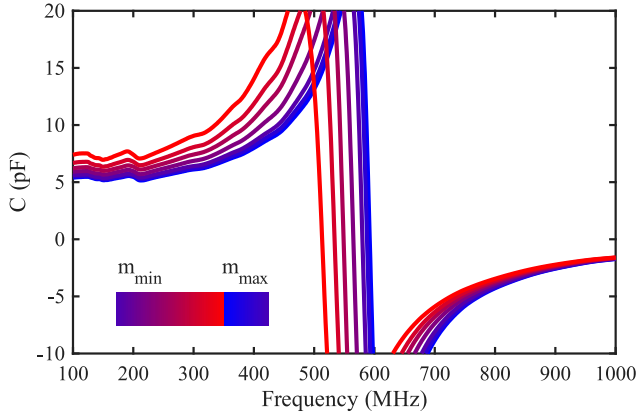


Fig. 5. Measured equivalent capacitance versus frequency under different mechanical loads. The color gradient represents the applied mass, where $m_{\min}$ corresponds to the unloaded state (0 g) and $m_{\max}$ to the maximum applied load (50 g).

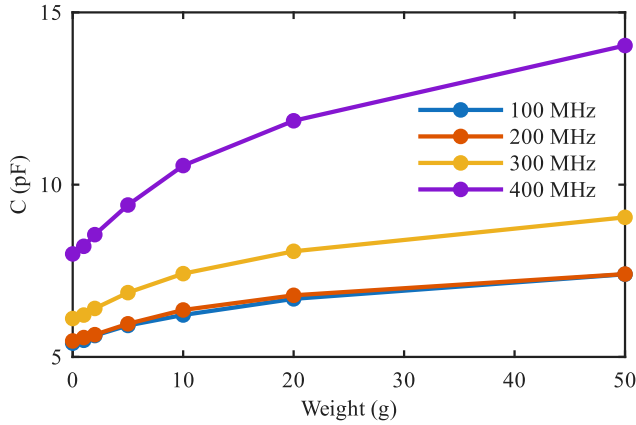


Fig. 6. Analysis of specific frequency in different weights.

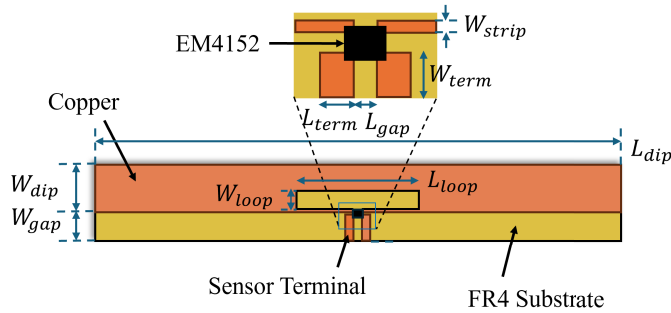


Fig. 7. Tag antenna geometrical parameters.

IV. UHF RFID TAG DESIGN

This section describes the tag antenna design and tag performance evaluation. The proposed tag design (Fig. 7) comprises an EM4152V001 IC which implements the radiofrequency interface where the antenna is connected and a capacitive measurement circuit to which the MLSC is connected. The IC exhibits a highly capacitive input impedance of $Z_{IC} = 24.7 - j284.3\Omega$ in the lower ETSI UHF band (865-868 MHz). The tag antenna was designed to be conjugate-matched to the IC impedance. To compensate for

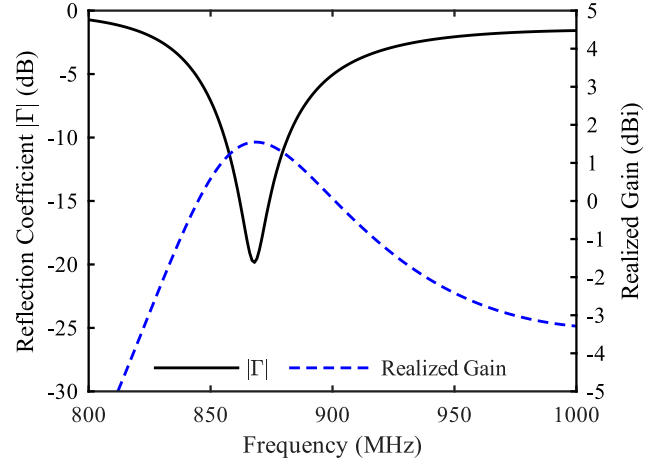


Fig. 8. Simulation results of the tag reflection coefficient and realized gain.

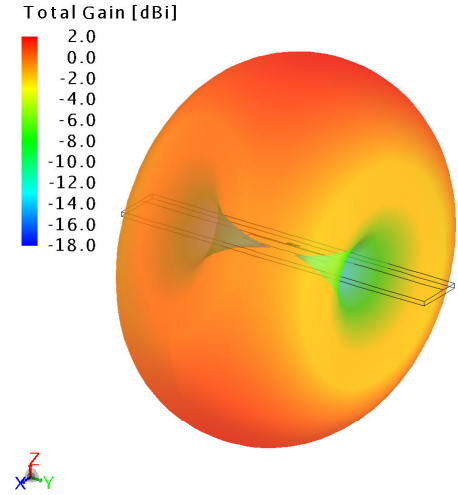


Fig. 9. Simulated radiation characteristics of the proposed RFID tag at 866 MHz.

this significant capacitive reactance, a T-match configuration was employed. The antenna geometry was optimized using Altair FEKO [26]. The prototype dimensions are presented in Table II. Fig. 8 shows the antenna-IC matching and tag performance evaluated through simulation values of the power reflection coefficient and the tag realized gain, respectively. The simulated power reflection coefficient exhibits a minimum of -19.1 dB and peak realized gain of 1.53 dB at the target frequency of 866 MHz. The simulated radiation pattern of the proposed tag at 866 MHz is presented in Fig. 9. As anticipated for a T-match dipole topology, the 3D total gain distribution reveals maximum radiation in the broadside direction, with a radiation null along the antenna axis.

V. WIRELESS SYSTEM VALIDATION

This section experimentally validates the proposed RFID sensing platform, integrating the textile-based MLSC sensor, the EM4152 IC, and the UHF RFID tag antenna. The following results demonstrate the performance of the fully assembled, battery-less system under realistic wireless interrogation conditions. First, the experimental setup is described,

TABLE II
GEOMETRICAL PARAMETERS (IN MM)

L_{dip}	L_{term}	L_{gap}	L_{loop}	W_{dip}
112.4	2	0.525	30.39	10
W_{strip}	W_{gap}	W_{loop}	W_{term}	
0.485	6	3.7	5.4	

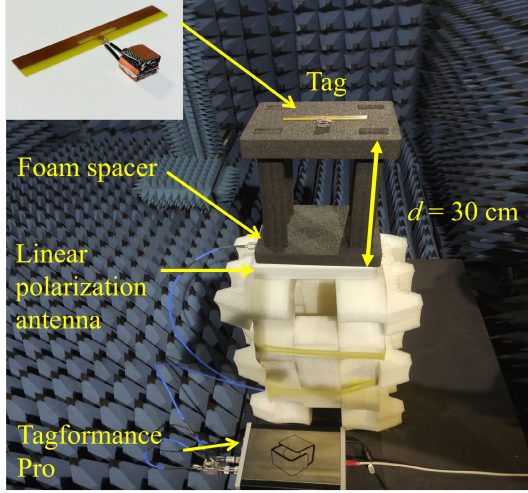


Fig. 10. Tagformance Pro measurement setup.

including the Tagformance-based read range evaluation and the real-time RFID measurement configuration. Then, the wireless sensing response under controlled mechanical loading is presented, followed by the calibration model that links the IC-reported capacitance to the applied pressure.

A. RFID Performance Evaluation

The tag read range was characterized using a Voyantic Tagformance Pro system inside an anechoic chamber (Fig. 10). The system measures the turn-on power [27] (P_{to}), defined as the minimum power transmitted by the reader that activates the tag at a fixed distance. Then, the tag realised gain $G\tau$ is computed from the turn-on power and the measurement distance. Finally, the theoretical read range d_{max} is calculated using the Friis transmission equation assuming perfect polarization coupling:

$$d_{max} = \frac{\lambda}{4\pi} \sqrt{\frac{EIRP \cdot G\tau}{P_s}} \quad (6)$$

where λ is the wavelength, $EIRP$ is the effective isotropic radiated power (in the lower ETSI band the EIRP is limited to 3.28 W), G is the tag antenna gain, $\tau = 1 - |\Gamma|^2$ is the power transmission coefficient, and P_s is the IC sensitivity.

Fig. 11 compares the simulated and measured tag read range. The results reveal a frequency shift in the peak performance: the measured maximum range of 13.3 m occurs at 855 MHz, whereas the simulation predicts 14.95 m at 866 MHz. This discrepancy is primarily attributed to the FR4 carrier used in the prototype. The inherent variability and higher dielectric losses of the FR4 material (compared to

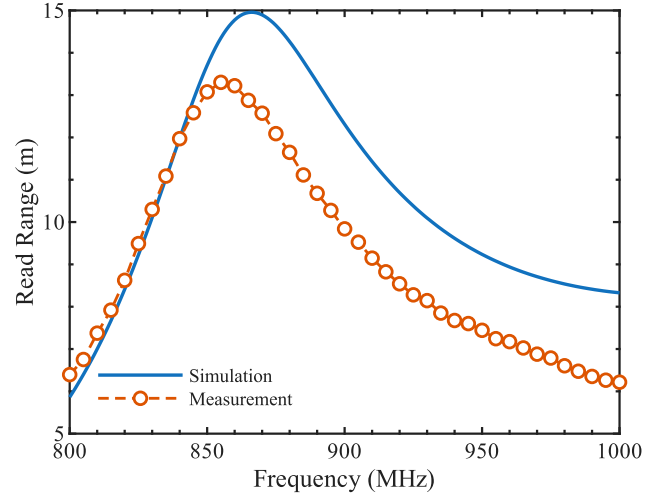


Fig. 11. Comparison between simulation and measurement values of the tag read range.

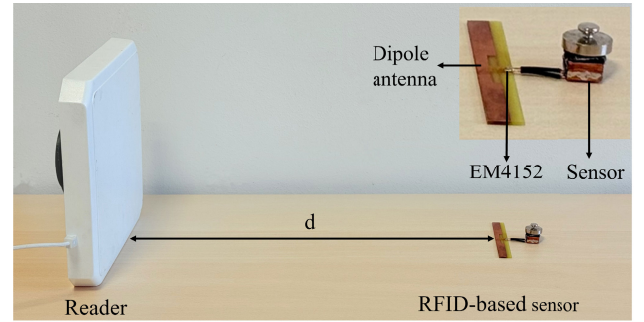


Fig. 12. UHF RFID measurement setup in which a commercial UHF RFID reader is connected to a circularly polarized antenna which illuminates the sensor tag from 2.3 meters distance.

the ideal simulation model) detune the antenna-IC impedance matching and reduce the overall radiation efficiency. Despite this shift, the tag maintains a robust in-band read range of approximately 13 m near the lower ETSI band edge, providing sufficient link margin for practical use.

B. Real-Time Wireless Sensing

The real-time sensing capability was evaluated by retrieving the capacitance reported by the IC from the reader. The measurement setup is shown in Fig. 12. The tag-reader distance d was set to 2.3 m to ensure far-field operation. The tag was continuously interrogated while discrete weights of 0, 1, 2, 5, 10, 20, 50, and 100 g were sequentially applied. The following results demonstrate the performance of the fully assembled, battery-less system under realistic wireless interrogation conditions. First, the experimental setup is described, including the Tagformance-based read range evaluation and the real-time RFID measurement configuration. Then, the wireless sensing response under controlled mechanical loading is presented, followed by the calibration model that links the IC-reported capacitance to the applied pressure. However, because the VNA infers an equivalent capacitance from RF reactance

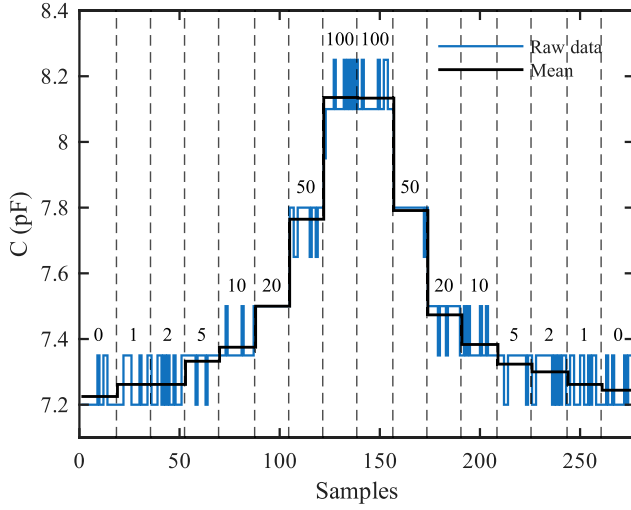


Fig. 13. Raw data and stepped average of the retrieved capacitance for one loading-unloading cycle.

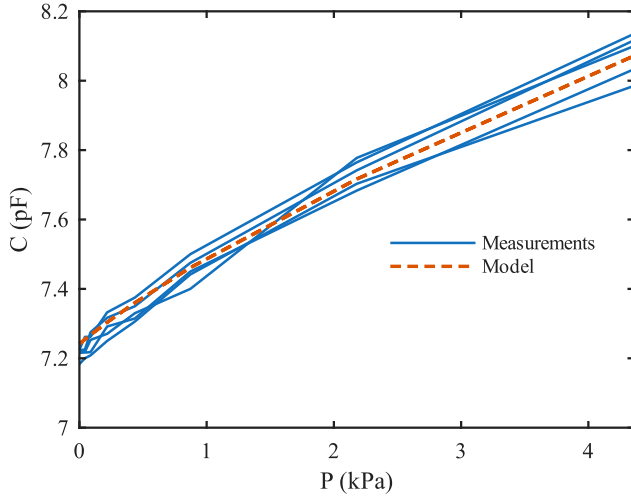


Fig. 14. Wireless capacitance calibration fit based on the compression of the multi-layer denim stack. The analytical model proposed in (5) is compared to the averaged capacitance values measured during 5 loading cycles.

whereas the RFID IC reports capacitance through its switched-capacitor front-end, absolute values need not coincide.

An example of a loading-unloading (LU) cycle is presented in Fig. 13, where the raw measurement data is plotted in blue. The capacitance is measured for each load during 20 s intervals and the averaged value is plotted as a black line. The experiment shows stable tag interrogation during each holding interval. The average capacitance increases monotonically from 7.22 pF at 0 g to 8.13 pF at 100 g. The identical average values obtained at 1 g and 2 g indicate that load discrimination is more limited in the very low-load region for the present dataset, whereas the overall response remains clearly monotonic over the full measurement span. No systematic drift is observed within each steady-state hold interval at the time scale of the experiment, confirming that the proposed platform is suitable for quasi-static wireless pressure monitoring.

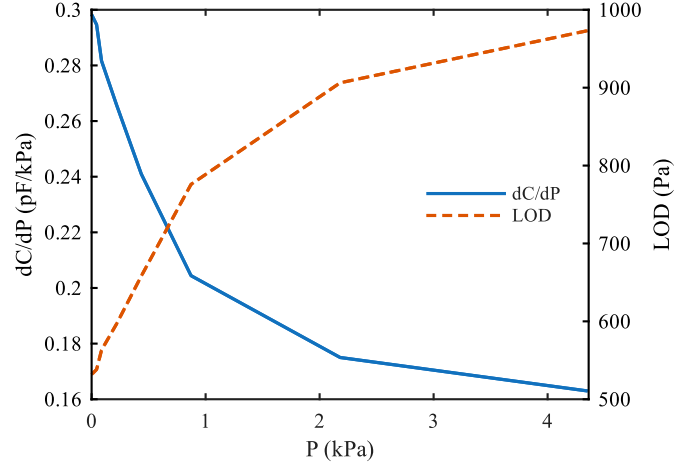


Fig. 15. Pressure-dependent sensitivity and corresponding limit of detection derived from the wireless calibration model.

Fig. 14 illustrates the measured capacitance averaged for each load in intervals of 20 s as a function of the applied load for 5 different loading cycles. The results show a sublinear response. These results confirm that the sensor exhibits a monotonic response characterized by progressive stiffening, avoiding a physically unrealistic linear infinite compression. The electromechanical model of (5) was fitted to the measurement data as follows: first, $\varepsilon_M(h_0) = 1.7$ was found using the transmission line method, where h_0 corresponds to the fabric layer thickness h in the unloaded state, and $\varepsilon_P = 1$. The volume fractions ($f_F(h_0) \approx 0.42$ and $f_P(h_0) \approx 0.58$) were found empirically infusing water into the textile-based MLSC until reaching saturation and $\beta = 0.45$ a fitting parameter ([19], [20]). Then, $\varepsilon_F \approx 3$ was computed from (2). C_{cal} was adjusted to match the initial capacitance at the unloaded state. Then, k and α were tuned to match the curvature of the measured data. The values obtained through this process are $C_{cal} = 2.7$ pF, $k = 412$ N/m and $\alpha = 2.75 \cdot 10^5 \frac{\text{N}}{\text{m}^2}$.

The fitted model reproduces the characteristic sublinear response observed experimentally, where capacitance increases with applied mass while the sensitivity progressively decreases. Residual discrepancies observed at intermediate and higher loads are attributed to unmodeled viscoelastic effects, hysteresis, and possible pressure-dependent dielectric variations.

This behavior is attributed to the compaction of the porous denim structure, which reduces air volume fraction and increases inter-fiber contact, leading to an effective stiffening of the material. This effect is modeled using (4). Fig. 16 illustrates the mechanical dynamics of the analytical model. The results show a slight deviation from laboratory observations, from which a compression of approximately 1 mm is expected after the application of the 100 g load.

VI. PERFORMANCE ANALYSIS AND BENCHMARKING

Based on the wireless calibration model established in (5), this section quantifies the critical performance metrics of the sensor system, focusing on sensitivity, hysteresis, resolution, and benchmarking against state-of-the-art textile sensors.

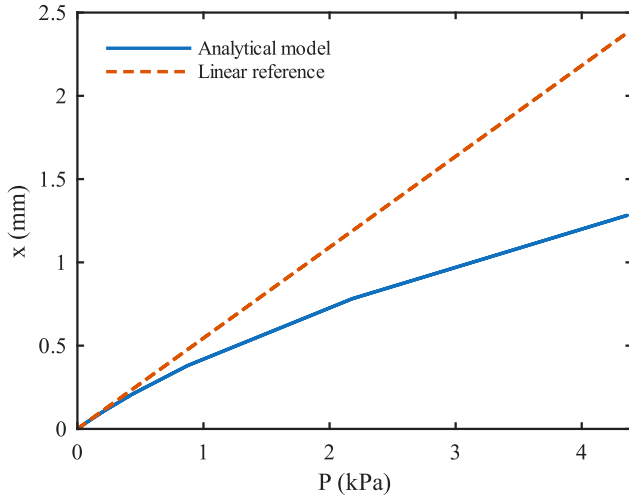


Fig. 16. Compression response of the multi-layer denim stack as a function of applied pressure estimated with the analytical model (4) compared with a linear reference.

A. Sensitivity Analysis

The sensor sensitivity S , defined as $S = \frac{\partial C}{\partial P}$, is plotted in Fig. 15. The results show that the sensitivity decreases progressively with increasing pressure. The initial sensitivity is approximately 0.3 pF/kPa, and it decreases to 0.163 pF/kPa at the upper end of the investigated range. The average sensitivity over the full measured range is 0.19 pF/kPa. These results indicate a gradual decay of the pressure dependence on the sensitivity as the textile structure becomes increasingly compacted.

B. Resolution and Limit of Detection

The effective noise floor, σ_{noise} , was extracted from the standard deviation of the capacitance measured during the steady-state unloaded (0 g) plateau. Then, the limit of detection (LOD) was calculated as

$$\text{LOD} = \frac{3\sigma_{\text{noise}}}{S} \quad (7)$$

Fig. 15 plots the computed LOD depending on the applied pressure. Using the experimentally determined noise floor together with the average sensitivity, the average LOD was found to be 833 Pa.

C. Repeatability and Hysteresis Analysis

To assess the repeatability and measure the sensor hysteresis a set of 5 LU cycles were performed over a sensor tag (s1) using the set of weights of Fig. 4. The mean (μ) and standard deviation (σ) of measured capacitance values for the five LU cycles are plotted in Fig. 17. The loading semicycle (L) is plotted as a continuous line and the unloading semicycle (U) as a dashed line. The results show that σ increases progressively as the pressure increases while a low hysteresis error is encountered throughout the measured range.

A second tag (s2) was fabricated to evaluate the repeatability of the manufacturing process. The findings in Fig. 17 illustrate a slight deviation from one sensor to the other through all

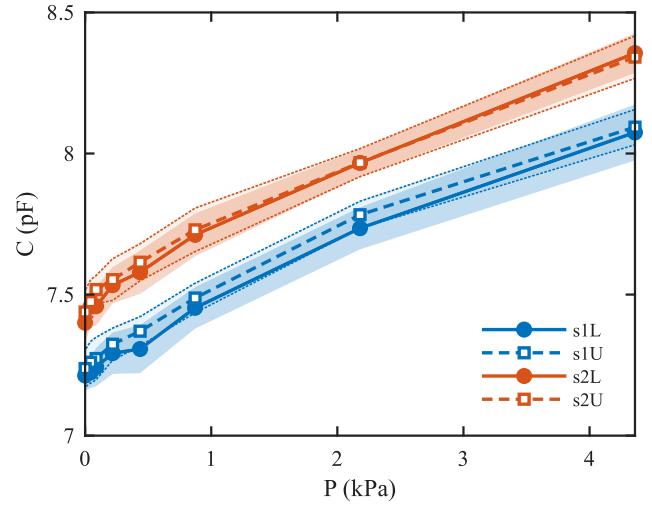


Fig. 17. Repeatability, hysteresis, and sensor-to-sensor variability of the wireless capacitance response under loading–unloading cycles. The responses of two tags are plotted: s1L and s1U correspond to Sensor 1 loading and unloading cycles, respectively, and s2L and s2U correspond to Sensor 2 loading and unloading cycles, respectively.

investigated loads while the non-linear behavior is preserved. This constant deviation can be accounted for through an initial calibration process of the analytical sensor model. The analytical model can be fitted to each sensor response by simply tuning C_{cal} through a loading cycle. Furthermore, industrial manufacturing is expected to reduce device-to-device variability and improve reproducibility, although this aspect is beyond the scope of the present study.

D. Comparison With State-of-the-Art

Situating this work within the current technological landscape, a structural comparison with recent passive wireless pressure sensors highlights the distinct advantages of the decoupled architecture (Table III). Conventional platforms frequently rely on antenna-dependent variables, such as fluctuations in the RSSI [9], [10] or resonant frequency shifts [7], to infer environmental pressure. While functionally viable in controlled settings, this paradigm inherently entangles the sensing data with the RF communication link, rendering the analog measurements highly vulnerable to environmental multipath fading and unpredictable dynamic shifts in tag orientation during movement. In addition, exploiting impedance mismatches for sensing purposes results in severely restricted read ranges below 5.8 m [10].

By firmly maintaining a stable conjugate match independent of the active sensing variable, the proposed MLSC platform effectively shatters this historical proximity constraint, achieving an extended maximum read range of approximately 13 m. This dramatic expansion represents a paradigm shift towards true room-scale monitoring, enabling practical, unobtrusive scenarios such as tracking a patient's vital signs or movements seamlessly across a standard clinical environment.

Beyond these compelling electrical performance metrics, the material composition of the sensor represents a critical leap toward realistic, everyday wearability. While specialized

TABLE III
COMPARISON OF REPRESENTATIVE BATTERY-LESS WIRELESS PRESSURE SENSORS

Ref.	Readout metric	Materials	Frequency	Read range	Sensitivity	Resolution	Pressure range
[7]	Frequency shift	PDMS metamaterial absorber	22 GHz	0.25 m	100 MHz/kPa	NA	0–55 kPa
[9]	RSSI	Tag-sponge-ferrite film	UHF	> 0.7 m	−9.49 dBm/kPa	NA	1.39–2.57 kPa
[10]	RSSI	Knitted textile + patch (compression)	UHF	5.8 m	NA	1-bit (1 dB)	NA
This	Capacitance	Denim/Copper	UHF	13 m	*0.19 pF/kPa	833 Pa	0–4.4 kPa

* Average sensitivity evaluated within the measured range.

synthetic elastomers, such as PDMS [7] or ferrite-loaded sponges [9], are frequently employed in literature to maximize absolute mechanical sensitivity, they intrinsically lack the vital breathability and structural comfort demanded by human apparel. By actively leveraging standard porous fabrics, such as denim, as the primary compressible dielectric, this system elegantly circumvents the limitations of impermeable synthetics. Although direct, seamless integration is currently constrained by the prototype’s physical profile, this architecture successfully validates the underlying electromechanical concept.

VII. DISCUSSION

The present design should be interpreted as a proof-of-concept demonstrator rather than a garment-ready wearable implementation. In this work, copper foil was selected as a simple and reproducible conductor to validate the sensing principle, the capacitive readout through the EM4152 IC, and the wireless RFID interrogation chain under controlled laboratory conditions. However, the current assembly was not designed to withstand washing cycles. In particular, the electrical interconnections between the sensing stack and the RFID chip constitute mechanically vulnerable points that may fail under repeated textile deformation or laundering.

For practical integration into daily clothing, several constraints must still be addressed. A key challenge is the trade-off between the initial sensor thickness and the achievable compression range, which directly determines the capacitance swing. Reducing the number of layers and the total stack height is essential to obtain a thinner and more comfortable structure that can be more naturally embedded into garments. In parallel, the current metallic interconnection strategy should be replaced by textile-compatible conductive technologies. In this context, flexible conductive inks and conductive threads are regarded as promising alternatives for future implementations integrating the antenna, the sensor, and the interconnect network into a unified washable textile platform. These developments, however, remain outside the scope of the present study.

Since denim is a porous and moisture-absorbent textile, environmental humidity and sweat may modify the effective dielectric permittivity and therefore affect the measured capacitance independently of pressure [19]. This effect may introduce cross-sensitivity in practical wearable conditions. In this work, the sensor is characterized under controlled laboratory conditions, and humidity effects are not experimentally

isolated. Future work will address compensation strategies for simultaneous pressure and moisture variations.

A key design trade-off in the proposed multi-layer textile sensor lies between mechanical thickness and electromechanical sensitivity. Decreasing the number of dielectric layers reduces the overall stack thickness, improving comfort and facilitating garment integration. However, this also limits the achievable compression range, resulting in a smaller capacitance variation and, consequently, reduced sensitivity and resolution.

Furthermore, maintaining a comparable nominal capacitance within the IC input range requires increasing the electrode area when fewer layers are used. In turn, a larger sensing area reduces the relative impact of localized pressure-induced deformation, as the effective contact region represents a smaller fraction of the total area. As a result, the overall sensitivity to applied pressure is further diminished.

Future development will focus on systematically miniaturizing the sensing element by reducing the overall thickness of the multi-layer stack while optimizing the fundamental trade-off among thickness, area, and sensitivity. This dimensional refinement, potentially supported by geometry scaling and the use of alternative textile-compatible materials, is expected to facilitate unobtrusive garment integration and enable thinner yet sufficiently sensitive wearable implementations for healthcare-oriented applications, including continuous light-touch monitoring and reliable fall detection in the elderly population.

VIII. CONCLUSION

This paper presented a fully passive UHF RFID-enabled capacitive pressure sensor utilizing textile fabrics as the dielectric medium. A denim/copper multi-layer stacked capacitor was fabricated and interfaced with a commercial RFID IC (EM4152) to enable IC-level capacitance readout. Experimental results validated the electromechanical response, demonstrating an average sensitivity of 0.19 pF/kPa in the measured pressure regime (0 to 4.4 kPa), alongside an empirical resolution of 0.5–1 kPa. Furthermore, the system achieved a maximum wireless read range of approximately 13 m in the lower ETSI UHF band, validating the potential for battery-less, room-scale sensing and surpassing comparable solutions found in the current state of the art. In addition, a complete electromechanical model has been presented and validated through experiments.

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