

# UHF RFID-Based Battery-Free Wireless Strain Sensor for EV Battery Management Systems

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**Abstract**—The development of wireless battery management systems (wBMS) for the next generation of electric vehicles (EVs) is increasingly gaining traction as a superior alternative to traditional wired BMS. Strain monitoring within lithium-ion battery cells is critical for assessing mechanical stress, which impacts state-of-charge (SOC) and state-of-health (SOH). This paper presents a novel idea of battery-free, wireless strain sensing system based on ultra-high frequency (UHF) RFID technology. The system features a flexible meander line inductor acting as RF strain gauge or sensing element (SE), integrated with a Magnus@-S3 M3D RFID chip. The chip's self-tuning capabilities to dynamically adjust its impedance to maintain optimal antenna matching are utilized to design a passive (battery-free) RFID based wireless strain sensing system. The SE when integrated with an RFID Tag antenna, operates well in challenging metallic environments like metal-caged EV battery packs, offers an interesting solution for wireless passive measurement of battery cell inflammation (strain). By employing polynomial fitting a precise correlations of SE's capacitance/inductance with SE expansion/contraction is established in this paper. The proposed system addresses limitations of traditional strain sensors, such as high power consumption, complex wiring, and limited scalability while eliminating the need for a dedicated power source, this approach provides a sustainable and efficient wireless passive solution for next-generation automotive wBMS using UHF RFIDs.

**Index Terms**—electric vehicles, strain Sensor, UHF RFID, wireless BMS.

## I. INTRODUCTION

Electric Vehicles (EVs) have emerged as a key solution for reducing carbon emissions and advancing sustainable transportation [1]. At the core of every EV lies its battery, which serves as the primary power source, directly influencing the vehicle's range, efficiency, and lifespan. Given the critical role of EV batteries, Battery Management Systems (BMS) are essential for monitoring, managing, and optimizing battery performance. A BMS ensures that each cell within the battery pack operates within safe limits, preventing overcharging, overheating, and other stressors that may lead to degradation or, in severe cases, failure [2]. To improve the scalability, cost and weight of the battery pack, EV industry is moving towards wireless sensing solutions such as wBMS [3], [4]. One crucial parameter that a BMS or wBMS must monitor is the mechanical strain within battery cells. Strain sensing provides crucial insights into battery cell integrity, as mechanical stresses fluctuate due to temperature variations, charging cycles, and aging. Accurately detecting strain allows

the BMS to adjust operational parameters, thereby extending the battery's lifespan, enhancing safety, and optimizing overall performance [5]. However, current strain sensing technologies,

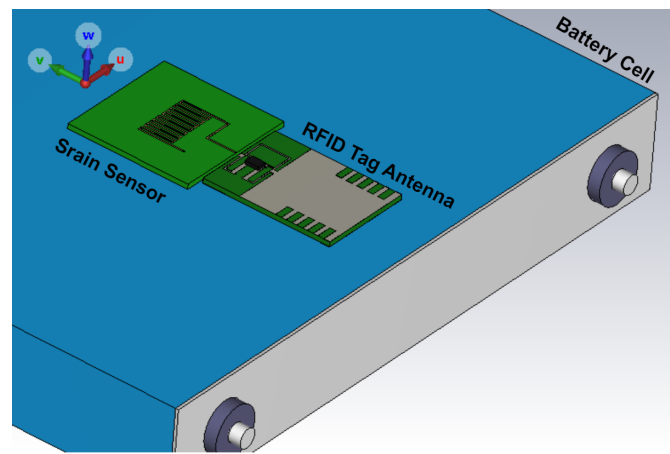


Fig. 1. Integrated RFID energy-autonomous strain sensor attached to battery cell

such as Fiber Bragg Grating (FBG) sensors [6] and hybrid sensors used for battery state-of-health monitoring, typically draw power from the EV battery, resulting in gradual energy depletion and a negative impact on overall EV efficiency [7]. Additionally, integrating conventional strain sensors into battery packs introduces challenges, including complex wiring and circuitry, which can create points of failure and limit scalability. Many existing sensors also struggle to capture real-time data accurately, particularly in harsh environments characterized by fluctuating temperatures and high currents, which are typical in EV applications [8].

These limitations underscore the need for an innovative, battery-free, wireless strain sensing solution. Leveraging RFID technology, battery-free strain sensors can operate without relying on power from the battery pack, instead utilizing energy harvested from an RFID reader [9]. This approach offers a more sustainable, compact, and efficient method for strain sensing, aligning with the evolving demands of next-generation EV battery management systems [10]. However, establishing successful wireless communication between the reader and RFID tag in fully confined metallic environments presents a significant challenge [11]. In this paper, we pro-

pose a wireless, battery-free integrated strain sensor based on UHF RFID communication for automotive wireless battery management systems (wBMS). The Magnus S3 chip based RFID tag antenna, integrated with a meander line strain sensor is attached to the battery cell as shown in Fig. 1. The design is optimized to operate effectively in harsh metallic environments, such as metal-caged EV battery packs.

## II. SENSING MECHANISM AND MODELING

Self-tuning RFID chips offer a groundbreaking solution for improving chip-antenna matching by dynamically adjusting the chip's internal impedance. Unlike conventional RFID tags, which are optimized for a specific center frequency and experience degraded performance when environmental changes alter the antenna's impedance, self-tuning chips maintain effective matching across a broader frequency range. This innovation ensures consistent performance even in challenging environments involving factors like metal objects or liquid content. A notable example is the Axzon Magnus@-S3 M3D chip [12], which features a Chameleon™ engine that automatically adjusts the chip's input impedance before communication begins. This is illustrated through simplified diagrams of the chip's structure and impedance-matching mechanism in Fig. 2. The self-tuning RFID chips are particularly suitable for applications such as battery cell monitoring. The Magnus-S3 M3D IC is compatible with EPC Class 1 Gen 2 v2.0.1 and ISO/IEC 18000-6C compliant readers, ensuring widespread usability. In this paper, we propose a novel idea of utilizing the self tuning capabilities of Magnus S3 chip to detect the mechanical strain on a battery cell in EV battery pack. This is achieved by integrating SE connected directly to a RFID tag. The sensor is entirely passive and does not require a separate power source to operate. The illustration in Fig. 2 describes how the chameleon Engine in Magnus S3 chip compensates the change in sensing elements reactance and in return reports a SENSOR CODE.

### A. Magnus S3 Chip Sensor Code

The Chameleon engine in the Magnus-S3 M3D IC plays a crucial role in quantifying impedance matching settings by generating a SENSOR CODE. This code, stored in 9 bits, can theoretically represent 512 distinct states ranging from 0 to 511. In practical applications, however, the code typically operates between a minimum of 5 and a maximum of 490. Optimal performance is observed when the Sensor Code lies within the range of 80 to 400, as read ranges tend to degrade slightly outside this range. The Sensor Code can be accessed via the READ command, stored in the nine least significant bits (C7h-CFh) of the Reserved Memory Bank, as detailed in the Magnus-S3 M3D Passive Sensor IC data sheet [12]. A deviation in SE width causes the Chameleon engine to dynamically compensate for variations in the SE's reactance. As a result of these adjustments, a SENSOR CODE is generated, directly linked to the variation in the SE's physical deformation. The SENSOR CODE, read by the RFID reader, quantifies the deviation in capacitance

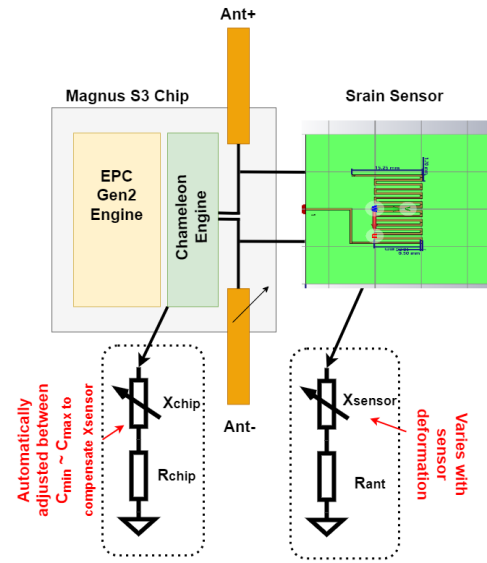


Fig. 2. EM4325 chip chameleon engine loaded with meander line strain sensor

mismatch caused by the SE deformation. By establishing the relationship between the SE deformation, represented by the Sensor Code, and the relative change in the SE's width ( $w$ ), it becomes possible to estimate the strain experienced by the battery cell. This approach enables real-time monitoring of mechanical stress on the battery, leveraging the RFID system's capabilities to deliver a non-invasive, data-driven solution for strain estimation and analysis.

### B. Internal Capacitance Tuning Range

To evaluate the tuning range of the Magnus S3 chip, the required capacitance is calculated using  $C_{req} = \frac{1}{\omega X_{ant}}$ , where  $C_{req}$  represents the capacitance necessary to tune the antenna's reactance back to its original position, as illustrated in Fig. 3. The chip's tuning range is defined by its minimum and maximum capacitance values,  $C_{min}$  and  $C_{max}$ , as specified for the Magnus S3.

The analysis focuses on the tag's read range, with tuning limits derived from optimal SENSOR CODE values ranging from 80 to 400, corresponding to capacitance levels between 2.056 pF and 2.68 pF (Fig. 3). The total chip capacitance, based on the SENSOR CODE, is expressed as  $C_{chip}(n) = C_{min} + n\Delta C$ , where  $C_{min} = 1.9$  pF,  $\Delta C$  is the incremental capacitance step, and  $n$  represents SENSOR CODE in range  $N_{min} \leq n \leq N_{max}$ .

### C. Relationship Between Capacitance ( $C_{chip}$ ) and Width ( $w$ )

To analyze the relationship between ( $C_{chip}$ ) and  $w$ , a parametric sweep was carried out across varying widths (stretching the sensor by approx. 10%, and the corresponding capacitance values were recorded. The widths  $w$  ranged from 0.6 mm to 1 mm, and the capacitance  $C$  was recorded in picofarads (pF) showed a decreasing trend with an increase in width  $w$ . Initial observations suggested a non-linear trend, leading

to the selection of a quadratic model for curve fitting. By applying polynomial regression techniques, a quadratic fit was derived, providing an analytical expression for capacitance as a function of width to model the relationship between the chip capacitance ( $C_{\text{chip}}$ ) and the width ( $w$ ) of SE, up to the 4th degree as follows.

$$C_{\text{chip}} = -0.1126w^2 - 1.3732w + 4.2815 \quad (2)$$

$$C_{\text{chip}} = -16.1616w^3 + 77.4632w^2 - 125.0176w + 69.7167 \quad (3)$$

$$C_{\text{chip}} = 23.3100w^4 - 165.3458w^3 + 434.5478w^2 - 503.8654w + 220.0348 \quad (4)$$

The width expansion required to achieve capacitance ( $C$ ) values between 2 pF and 2.8 pF varies based on the polynomial fit degree. For a second-degree polynomial fit, the width ( $w$ ) values are 1.4816 for  $C = 2$  pF and 0.9974 for  $C = 2.8$  pF. For a third-degree polynomial, the corresponding values are 1.4667 and 1.2669, while for a fourth-degree polynomial, they are 1.4643 and 1.2881, respectively. These variations indicate the sensitivity of width expansion calculations to polynomial degree selection.

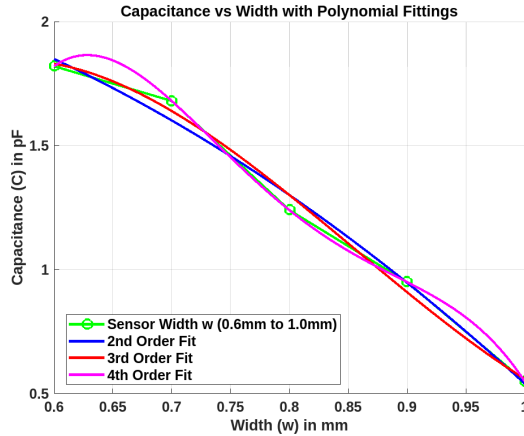


Fig. 3. Relationship between  $C_{\text{chip}}$  and  $w$  plotted at 866.5 MHz

### III. RESULTS AND DISCUSSION

The sensing element integrated with the tag antenna was simulated using the CST Microwave Studio software. The meander line capacitor was stretched along its width (Y-axis) from 0.6mm to 1.0 mm. The expansion of sensing element length resulted in a change in antenna impedance reactive part as shown in Fig. 3 and Fig. 4. It can be seen that the length variation fall within the acceptable tuning range of Chameleon engine. The generated sensor code ranges from 80 to 400, directly reflecting the amount of stain according the the equation (2), (3) and (4). Using the relationship between the expansion of flexible sensor and corresponding SENSOR CODE acquired through self-tuning chip, the battery cell

expansion during the charge discharge cycle can be predicted with reasonable accuracy.

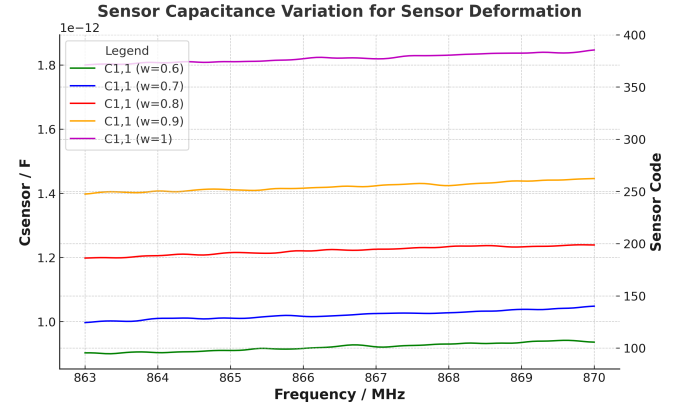


Fig. 4. Resulting change in antenna capacitance when sensing element is stretched for  $w$  from 0.6mm to 1.0mm

### IV. CONCLUSION AND FUTURE WORK

In this paper, a novel approach to estimate the strain on battery cell of an EV battery pack is presented exploiting the self-tuning capability of Magnus S3 RFID chip. A flexible meander line inductive sensing element is developed and feasibility of using it for strain sensing is analyzed. The approach is energy autonomous, wireless and extremely cost effective as compared to the traditional methods used for battery cell strain to predict the cell SoH and life span.

As a future work, authors plan to design a metal-mountable RFID tag for Magnus S3 chip, suitable and optimized for fully metal enclosed EV battery pack. The tag will be integrated with the sensing element discussed in this paper. The whole system will be deployed on an actual battery cell used in EV battery pack and verify the simulation observations obtained in this research.

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