Next-Generation Battery Management Systems: Integrating RFID for Battery Passport Applications

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***Abstract*—With the rapid growth of electric vehicle (EV) production, efficient battery life cycle management has become increasingly critical, especially as the demand for second-life battery applications is mandated considering environmental aspects. The European Union's introduction of battery passports, aimed at enhancing battery traceability, presents new challenges for existing Battery Management Systems (BMS). The proposed solution of QR code tracking shows drawbacks when addressing scalability, local real-time monitoring, and data security concerns. Our work implements RFID technology as an extension of modular BMS architectures designed to meet the evolving requirements of battery passports and second-life battery use cases. By integrating NFC tags and leveraging this technology, the system enables secure, real-time data transmission between battery pack components and external readers, overcoming the limitations of QR codes. A demonstrator setup based on automotive-grade components validates the system's capability to monitor static and dynamic key battery parameters. The proposed solution offers a forward-looking approach to battery management, aligning with upcoming regulatory requirements while advancing the adoption of second-life battery management.**

***Index Terms*—Battery management system, Battery passport, Second-life, Security, Sensor, Near-field communication, RFID.**

I. Introduction

Changes at a global level have created an awareness of energy sustainability, which has led to increased investment in electric vehicle (EV) research and development, among other things. An exponential increase in EV sales has been observed around the world, with the numbers expected to rise even further, especially in the USA and China [1] (Fig. 1), where better subsidies and new battery inventions have led to degressive prices across EV production [2], [3]. The main driving components behind EV are the battery cells and battery management systems (BMS), which are responsible for safety and operational control [4]. Together they form a mechanical ecosystem that supports the EV powertrain.

However, such an exponential increase in the production of EV also correlates with an exponential increase in the production of battery cells. One problem that will arise in the coming period is the need to recycle such a large amount of battery cells, which is considered complicated, costly and, above all, harmful to the environment [3], [5], [6]. In response to these concerns, the European Union (EU) has begun to push

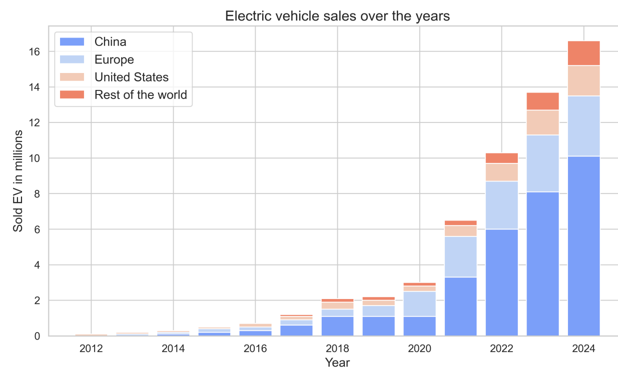

Fig. 1. Chart showing the number of sold EV globally in the last decade [1].

ahead with legislation to introduce "*battery passports*" [7], [8]. Similar to real physical passports, battery passports are intended to contain data tied to a specific battery pack. Battery passports would include: (i) static data - particular production information of the adjacent battery cells, but also (ii) dynamic data - which depends on the used battery topology and their use case in the actual application, e.g., EV. "*Second-life battery*" is a concept that describes the secondary use of battery cells after their primary use, i.e., after deemed unusable for EV. Albeit different, both battery passports and second-life battery concepts depend on each other. The solutions developed for battery passports should also consider second-life battery use cases and vice versa.

Battery passport challenges. The current market solutions for BMS and battery cells do not necessarily have the infrastructure and technology ready to fit the requirements proposed by the battery passport regulations. This is especially true for the second-life battery use case, for which the necessary technology needs to be provided that would allow a seamless transition between their primary and secondary applications while at the same time being easy to use, efficient, and secure. We need to provide an interface that can utilize modern security solutions both from the hardware and software perspective to protect battery data from being manipulated or counterfeited. The current proposals from the EU legislation which include a QR code with every battery pack are deemed inadequate from a security perspective and also for providing additional channels for battery cells' dynamic data collection.

RFID solution. We want to primarily focus on the wireless BMS, as the next-generation BMS to be used in EV. Wireless BMS have seen a surge of interest from both academia and industry in recent years making the use of long and heavy wires obsolete and improving with the reduced cost, maintenance, and increased production efficiency [9]. Here, we focus on the current SotA in the RFID technology [10], specifically the near-field communication (NFC) [11]. We believe that NFC is a suitable candidate for next-generation BMS device tracking as it offers access to easy and off-the-shelf applications that can be used with second-life tracking applications conforming to the battery passport requirements. Current solutions on the RFID use with BMS primarily focus on their technical aspects. We want to extend this and argue their use with battery passports by also realizing a full system design demonstrator.

Contributions. We are the first to consider and propose a design methodology for using RFID, specifically NFC technology, to supplement the requirements of the upcoming battery passports and second-life applications. We extend on the previous work by showcasing the feasibility of the proposed next-generation BMS design by building a demonstration system based on the three main use cases defined for the BMS NFC system design [10] by also considering the full battery lifecycle data transmission from the battery cells to the OEM cloud systems required by the battery passport legislations [12], [13].

II. Battery Passport Requirements

Background. One major problem with Li-Ion cells as used in EVs is their chemical aging, which disqualifies them from use in EVs as soon as the maximum battery capacity falls below a certain threshold (70-80 %). However, the battery might still be usable in other applications also requiring large electrical energy storage capabilities but less demanding in terms of performance and energy density. The concept of reusing batteries in another, less demanding system is generally referred to as "second life for batteries" [14].

Legislation. To support this concept, the European Union (EU) introduced the concept of "battery passports", a type of electronic record, unique to each battery, storing static and dynamic information in various information categories. By enforcing this regulation, a battery passport is mandated for batteries from February 2027 [7]. The use of QR codes is suggested as an implementation of a tracking mechanism. However, while QR codes are cost-effective and simple to implement, they are limited in functionality, scalability, and security. For instance, QR codes require direct visual access, making them inefficient for automated, real-time tracking and monitoring of battery health during both active and inactive use. Furthermore, the static nature of QR codes restricts their ability to support dynamic, real-time updates, which are essential for modern BMS solutions.

Execution. Berger et al. [13] determined 54 data points required for a battery passport in EVs covering four data categories: (i) battery, (ii) sustainability and circularity, (iii) diagnostics, maintenance, and performance, and (iv) value chain actors. Our work mainly contributes to the data points under (iii) as we focus on the transmission of stand-alone physical dynamic battery parameters as well as algorithmically calculated values giving more descriptive information such as State-of-Health (SoH) and State-of-Charge (SoC) [15]. Referring to [13], we cover levels 3 and 4 in the *Battery diagnostics* data scheme by employing transmission of the parameters mentioned above, amongst others on battery cell, module and pack system level.

III. RFID-Based Architecture for the Next-Generation BMS

In this work, we propose a system employing direct communication for diagnostic data with the battery pack instead of the proposed indirect solution by EU legislation of using QR codes for data readout. NFC is an ideal choice for addressing the scalability, real-time data requirements, and security issues inherent in the EU's QR code proposal. Operating at a frequency of 13.56 MHz, NFC allows for short-range wireless communication (up to 10 cm), providing a balance between range and power efficiency [11]. In comparison to e.g. Bluetooth Low-Energy (BLE), the restricted connection distance also enables additional security due to the requirement of being physically near the battery pack when establishing transmission as an external communication partner. More importantly, it can be integrated seamlessly into the BMS to monitor batteries during their active use in EVs as well as during idling and active times in second-life applications. This eliminates the need for continuous manual interventions or direct visual access to QR codes while monitoring batteries during storage, ensuring safe battery conditions. Additionally, to supplement the need for infrastructure, many portable devices today, e.g., mobile phones, support NFC out-of-the-box. This would allow seamless integration of applications for the OEM cloud and user connection to facilitate the backend operations of the battery passport data storage and processing.

IV. Wireless BMS Demonstrator

By designing and implementing a demonstration system setup, we can validate the feasibility of our approach. The setup extends a modular BMS architecture by introducing NFC interfaces at multiple system levels to optimize internal and external communication paths.

A. Architecture

The BMS controller is central to the architecture, responsible for monitoring and calculating battery parameters such as cell voltage, cell temperature, SoC, and SoH. It communicates with the Battery Pack Controllers (BPCs), which manage individual battery packs. Complementing this established modular architecture, we equipped the components with NTAG devices, which are passive RFID tags operating on NFC technology.

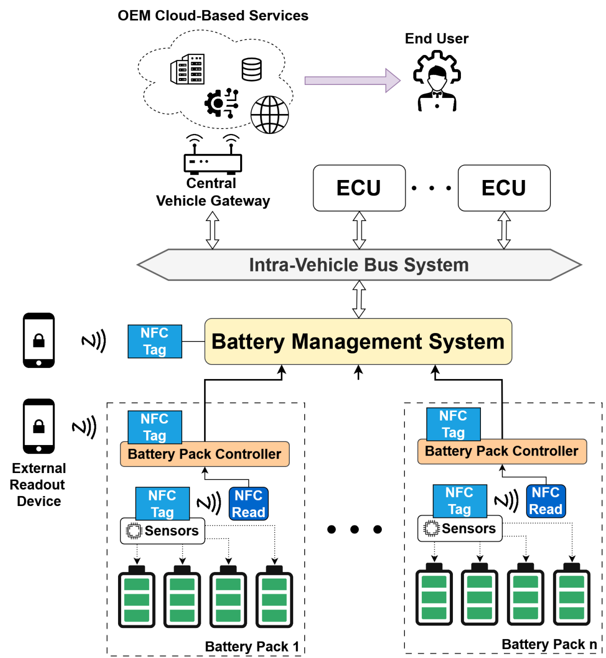

Fig. 2. NFC-equipped BMS architecture and communication paths.

Fig. 3. Wireless BMS demonstration build for battery passport readout.

These NTAGs store critical battery data and provide wireless connection interfaces to external NFC readers, thus bridging the gap between the internal battery system and external readout devices. The architecture design is detailed in Fig. 2. NFC communication channels are introduced (i) on the sensor level, (ii) on the BPC level and (iii) on the BMS level. The communication flow of the architecture developed in this work arises at the cell sensor level, employing NFC transmission as the main data channel for fundamental battery parameters, covering cell voltage and temperature. Multiple units are condensed on BPC and BMS layers respectively, purposed to resemble a modular BMS architecture. Each BPC and the single BMS are equipped with an NTAG, allowing wireless connectivity between the battery pack and NFC-enabled external readout devices. The resulting interfaces enable the gathering of collected data from multiple subordinated components. A permanent interface for connecting with remote processing systems is established via the intra-vehicular bus system, offering the central vehicle gateway as a battery management data bridge. This architecture design complies with requirements proposed by EU legislation [7].

B. Implementation

To implement the architecture proposed, we constructed a hardware setup that closely mimics a real-world scenario. The system utilizes automotive-grade hardware from NXP Semiconductors and components from the Raspberry Pi Foundation, as detailed in Table I, and partially described in previous work [10]. With this implementation, information security was also regarded based on the established vulnerabilities found within short-range wireless technology, i.e., for RFID [16]. A security suite was integrated by establishing secure communication channels tailored to their respective transmission requirements as previously described by Basic et al. [12]. The final configuration showcases a single representative battery pack strand for demonstration purposes, pictured in Fig. 3.

TABLE I
HARDWARE COMPONENTS USED IN THE BMS RFID DEMONSTRATOR.

Make	Model	Hardware Type	Role
NXP[a]	S32K144	General Purpose Microcontroller	BMS Emulator
NXP	MC33771C	14-Channel Battery Cell Controller	BPC
NXP	BATT-14C EMULATOR	14-Channel Battery Pack Emulator	Battery Pack Emulator
NXP	NCx33xx series	NFC Tag & Reader	NFC Wireless Connectors
RPF[b]	Pi4B	Single-Board Computer (SBC)	Gateway Emulator

[a]NXP Semiconductors
[b]Raspberry Pi Foundation

V. Evaluation of the Proposed System

Evaluation of the system is conducted concerning the conceptualization of the battery passport by Berger et al. [13]. The parameters required for a battery passport consist of static and dynamic data points.

A. Dynamic data

As our demonstration setup directly measures emulated cell voltage and cell temperature, we can state parameters as State-of-Charge (SoC) and Depth-of-Discharge (DoD) as directly supported from hardware side when applying appropriate calculation algorithms to the measured physical parameters. Regarding the remaining parameters of the *Diagnostics, Maintenance and Performance* category, fundamentals are laid with the proposed setup as a proof-of-concept. Parameters State-of-Health (SoH), Remaining useful Lifetime (RuL), range, lifespan and energy consumption require the availability and processing of further internal data available only at a higher technology readiness level. Maintenance-related data points require external communication with service tools, except for the record of internal event triggers. For this application purpose, bidirectional external data communication with NFC-enabled devices might become a topic of relevance in future research. These evaluation results are summarized in Table II.

TABLE II
INTEGRATION OF DYNAMIC BATTERY DATA

Data point	Data category	Integration
SoH	Battery health	∼
SoC	Battery health	✓
DoD	Battery health	✓
RuL	Battery health	∼
Range	Performance	∼
Lifespan	Performance	∼
Energy consumption	Performance	∼
Maintenance/ Repair measure	Maintenance history	✕
Trigger	Maintenance history	∼
Responsible party	Maintenance history	✕

✓... fully implemented
∼... fundamentals for processing implemented
✕... system extension required

B. Static data

The remaining data points stated by Berger et al. [13] comprise the data categories *Battery*, *Value chain actors* and *Sustainability and circularity*. Those categories exclusively contain static values. The internal memory of the BMS controller can serve as a storage or buffer location for these. Since it is integrated as the central component of the BMS, the data could be transferred to an external readout device without necessarily demanding a connection to remote services as opposed to the static solution of scanning QR codes.

VI. CONCLUSION

We explored the challenges and potential solutions associated with the introduction of battery passports, a new regulatory requirement aimed at improving the traceability, security, and management of electric vehicle (EV) batteries throughout their lifecycle. As exponential growth in EV production is expected, effective battery management is becoming increasingly critical, particularly as second-life applications gain importance. Current methods in discussion, such as QR code tracking, seem inadequate due to their limitations in scalability, availability, security, and real-time data transmission.

Tackling these challenges, we have proposed a novel BMS design, employing RFID, particularly NFC technology at crucial interfaces. Our system addresses the deficiencies of approaches employing QR codes as data interfaces by offering secure, local, and wireless data transmission, suitable for both primary EV applications and second-life scenarios. The implementation demonstrates how NFC interfaces, can be effectively integrated into BMS architectures, ensuring continuous monitoring and secure data transmission from battery cells to external readout devices and cloud systems while regarding relevant static and dynamic parameters.

Through the development of a modular architecture and demonstrator setup, we validated the feasibility of NFC for dynamic battery parameter tracking. Our solution not only aligns with upcoming EU battery passport regulations but also improves capabilities in battery life cycle management, paving the way for further innovations in second-life battery applications and the broader EV ecosystem. Future work will focus on further enhancement of interfaces to create a uniform and industry-ready solution, focusing on compliance with current legislation.

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