Master degree thesis in Automotive Engineering - Autonomous and Connected Vehicles

Deformation modeling of cylindrical cells and wireless management system for direct cooled battery packs

Relatore:
Prof. Angelo Bonfitto

Co-relatore:
Prof. Vittorio Ravello

Candidato:
Lorenzo Campanella
mat. 315141

Academic Year 2024/2025

Contents

List of Figures

1 Introduction to communication technologies onboard EVs

1.1 Brief overview over EVs

Electric vehicles are not a novelty of the last decade, back between 1900 and 1910 they represented 38 % of the automotive market share, lead by steam vehicles at 40 %, while gasoline engine powered vehicles represented only the 22 %. Starting from the 20's problems related to short range, long time of recharge and problems of reliability of the batteries, lead to a fast misapprehend of such vehicles. A brief interest over such technology re-appeared in the 70's as alternative solution to face the petrol crisis of that time, but just at research level.

A real first tentative on putting over the market a mass production EV was done by GM back in the 90's, with the GM EV1 which was the first vehicle following the California Clear Air act, issued in 1988. Unfortunately, such regulation was particularly strict at that time, considering the technologies available back in that years and in fact the sales of the EV1 lasted only three years, from 1996 to 1999.

The evolution in battery technologies, with the introduction of Li-Ion batteries, the important development of power electronics devices like converters and inverters, gave the opportunity to EVs to slowly regain ground in the automotive market, starting from the last decade. Obviously, aspects like the still longer recharge time if compared with re-fueling time, the lower range, the higher cost and also the higher initial investments still slow down the spreading of EVs.

For sure, the most delicate and expensive component of an EV is the high voltage battery pack, which can be made from 4 to 24 modules, reaching also voltages of 700,800 or even 1000 V. It's clear that a battery management system (BMS) is necessary to properly manage the battery pack in terms of cells voltage, pack voltage, SOC, SOH and battery temperature.

So, it's clear that the battery electronics must operate at such high voltage and must be able to reject the voltage common mode, while differentially controlling and measuring each cell. The cells SOC and SOH are calculated indirectly from the measurements of voltage and current done by sensors mounted over the cells and communicating with the BMS. It's important to underline the fact that the usable range of the batteries is not 100 % but is limited to 70 % to avoid problems of fast aging. Moreover, considering also the +- 5 % of uncertainty of sensor readings, such value drops down to 60 %. So, it is important to underline how the sensitivity of sensor readings can deeply impact the usable range of the battery SOC and so the entire vehicle range and, for the same range to travel, the pack dimensioning and entire weight of the vehicle.

Another important aspect to preserve the health of the battery pack is the topic of the cell balancing. While charging and discharging the battery pack, it is important keep the SOC of all the cells more or less the same and this can be done in two ways: passive and active. The passive method historically is the oldest and allows balancing only during charging, using a simple shunt resistors which cut-off the cell as soon as it's fully charged; instead, during discharging the cell with the lowest SOC is the one which limits the entire range of the pack. The active method, which is the newest, instead uses electronic circuits to balance and equally re-distribute the SOC of all the cells in the pack.

In 2008 the first high performance multicell battery-stack monitor, the LTC6802 from Linear Technology was introduced and it was able to perfrom active balancing of 12 cells, by using a 12 bit multiplexed analog to digital converter. Newer solution usually make use of two 16-bit ADCs, one used to monitor only the cell voltages and the second used for ensuring functionally safe operations. The continuing monitoring of the cells by ADCs avoids problems of aliasing from input dead times inherent to multiplexed ADC solutions. This feature, as well as on chip digital filtering, improve measurements accuracy for up to 16 channels, even in noisy environments. In addition to measuring cell voltages, the monitoring ICs connect to thermistors that measures the temperature throughout the cells and also helps on improving the quality of SOC calculations and provide support on acting against over temperature situations.t. The BMS controller may also be connected to a pack monitor IC providing current measurement, coulomb counting, overcurrent detection, position of master disconnects, isolation resistance, and other features across the entire battery stack.

Robust communication systems are necessary in such environments that are particularly disturbed by electromagnetic interference EMI. Typically a wired bidirectional isolated serial port interface system is utilized and isolation barriers, such as capacitors, or pulse transformer are necessary.

1.2 Wired BMS

The battery pack of an EV is a quite delicate component and it provides energy to the electric motors and also to other auxiliary components. This makes clear that the usage of the battery pack should be performed with criteria in order to not damage it or subject it to dangerous conditions like over/under voltage/current and over/under temperature. To properly control its operations a micro controller unit (MCU), which properly uses data like cells voltage, current and temperature and from them evaluates state of charge (SoC), state of health (SoH), battery pack voltage and current and properly selects the control strategy to use, it's required. The voltage, current and temperature of each cell is measured through cell boards (CMBUs). Cell boards can be mounted one for each cell or they can be installed at module level. For sure, installing a cell board for each cell provides the most accurate values of V,i and T. The main drawback of a classic "wired" BMS system lays on the complexity of the overall system, the improved weight due to the presence of communication and power cables and and improved risk of electromagnetic interference. This kind of control topology is a classical master-slave configuration, where the master is represented by the BMS which requires info from the slaves and defines the control strategies, while the slaves are the cell boards. The safety management

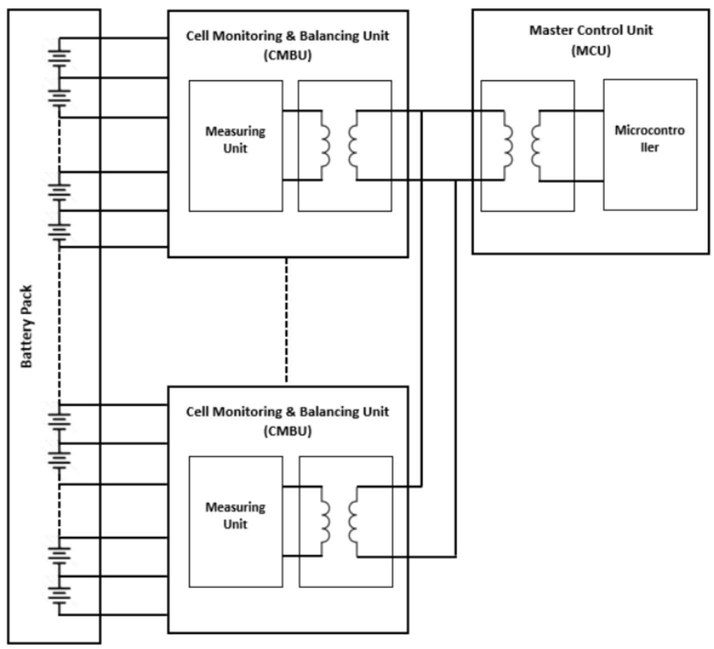


Figure 1: Example of structure of a "wired" BMS

of a BMS is one of the most important concern in battery industry. For ensuring battery safe operations several codes, software and standards are prepared and followed. Although batteries are, at the moment, the most convenient form of energy storage systems, accidents continue to happen. So, as a result, design basis scenarios must be considered in order to eliminate the risk. It is important that BMS ensures that battery pack stays always within the operational limits via bus communication. BMS must be able to maintain the on/off requirements for the main contactor, current, voltage and temperature profiles. BMS should support battery in technical, operational and safety criteria. If an external power source provides energy to the BMS, this energy must be recorded and included in the safety functions.

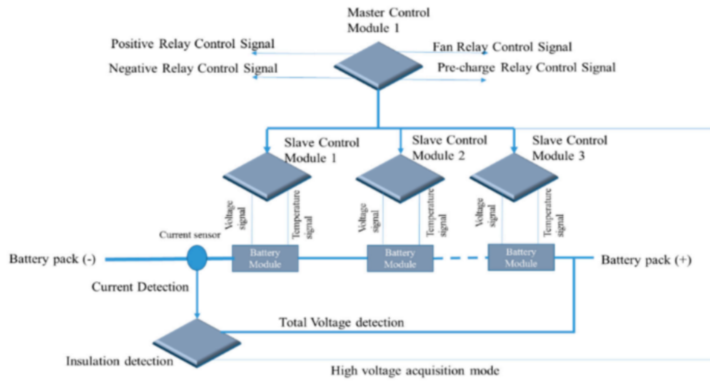


Figure 2: Master-slave architecture of BMS

The behavior of a BMS should be tested for overcharge/over-discharge conditions in order to validate the behavior with integrated passive circuit protection. In addition, cell overheating with an inhibited battery pack cooling control function should be secured. The goal is to validate the BMS checking that it will disconnect the battery from the main contactor and it will activate an active safety system with fire extinguisher in case of over-temperature conditions. For ensuring safe integration and operation every BMS must have a manual where all the safety constraints and details about software, hardware are defined.
Chemical characteristics are one of the most dominant causes of battery accidents. For what concerns the temperatures, generally the ones that are measured are two: electrochemical reaction temperature and battery environment temperature and they must be controlled for ensuring correct BMS operations. BMS development has stemmed from the emergence of lithium-based batteries, which unlike the conventional nickel-based batteries, do not tolerate any over voltage and may require secondary functions to work safely. Two relevant functions for a BMS are networthy:

- Overvoltage protection, a safety-related battery protection action.
- Accurate cell balancing, a function in the service of energy storage performance optimization.

Hazard in a BMS can be caused by the environment in which it operates and by the internal and external equipment. The hazard analysis defines, potentially, two main types of risks:

- Chemical, environmental and electrical hazards resulting from the operation of the BMS;
- Hazard resulting from the BMS operating within the battery system;

In the moment in which the hazard analysis has been performed, it is necessary to perform two steps: select the type of hazard to be mitigated by the BMS action and estimate the risk associated with the above-mentioned hazards, based on their probability and severity. Obviously, this stage depends a lot on the type of battery, on the technology, on battery system developer and future integrator or operator.he quantitative and semi-quantitative techniques are applied to measure and relate safety integrity levels (SIL) to risks. Risks estimated through preliminary analyses should be compared to evaluate their tolerable rates of occurrence (THR). These rates determine the SIL attribution to corresponding safety functions.
Heat deeply affects the performances of battery cells. Excessive heat can evaporate the electrolyte's liquid reducing significantly the cells performance, causing a permanent damage to the battery pack. Heat speeds up the speed of the chemical reaction happening inside the cell, while cold temperatures slow down the kinetics. Another way to permanently perform a battery cell is to operate it above and/or below the rated voltage. Similarly, operating in undercharge and overcharge conditions causes permanent damage. In particular, in overcharge conditions, the additional current will flow through the battery and decomposes the water in the electrolyte. Instead, undercharge causes low current flow through batteries, and the chemical remains in the battery plate, causing a significant amount of capacity loss. Another cause of permanent damage for a battery cell is for sure short circuit and it happens in the moment in which positive and negative enters in contact due to the presence of a low resistivity or high conductivity, causing a huge amount of current flowing through the cell. The loss of communication between the control units also causes failure in BMS since the control units are interconnected among them.

	Potential Hazards Related to BMS Operation within the Battery System
1.	Loss of air conditioning and battery cooling (BSS—battery support system).
2.	Loss of battery heating controls (BSS).
3.	Loss of battery voltage control function (BMS/EMS).
4.	Over-discharge of cells due to a ground fault or control function loss (BMS/EMS).
5.	Overcharge due to control function loss, data drift or software error (BMS/EMS).
6.	Over-current due to control function loss or shunt calibration error (BMS/EMS).
7.	Short-circuit in control and diagnostic cabling on the battery (BMS).
8.	Loss of communication between control systems (BMS/EMS).
9.	Loss of BMS/BSS functionality.

Figure 3: Example of typical BMS hazards

1.3 The wireless revolution

Wired system of communication between cells and BMS brings many complexities, like a huge amount of human labor for cabling all the connections, an improved weight of the entire battery system and so of the EV, an important reduction of the available volume and roominess inside the vehicle and problems of electromagnetic interference.

The idea of introducing wireless communication technologies, for allowing BMS and cell boards to exchange information, brings potentially many advantages, like: reduction of the total weight of the EV, improved resistance against electromagnetic interferences thanks to the presence of air gaps that acts like barriers and an important reduction of the cost, time of manufacturing and production of the entire battery system, together with a reduction of 90 % of the wires used and a reduction of 15 % of the volume occupied.

Wireless system of communication allows also to improve the modularity of the entire battery unit, since the same set-up of modules and trans-receivers can be installed onboard many different fleets of EVs, without any problem. Instead, wired solution are highly personalized and developed for a specific fleet of EVs, reducing the modularity. Similarly, when the vehicle comes to its end of life, wireless modules are easily repurposed in second-life applications in energy storage instead being scrapped and recycled at high cost.

It's clear that radio communications for a wireless BMS must be strong and reliable enough against all the possible interference scenarios. So, safety considerations require the automobile and the battery to be put in a safe state. Among the different sources of interferences there are legal WiFi, Bluetooth, terrestrial broadcasts, radar, cell phones and also malicious jammer. So, is important that radio links are kept at a strong received power, around -50 dBm to -60 dBm. Since a Wireless BMS (WBMS) operates with substantial in-band interference, radio-links with order of magnitude higher than thermal floor are necessary. When there are powerful interferences, to ensure reliable operations, radio may be optimized to include high power tolerance, wide band linearity and close in linearity coupled with a large base band dynamic range.

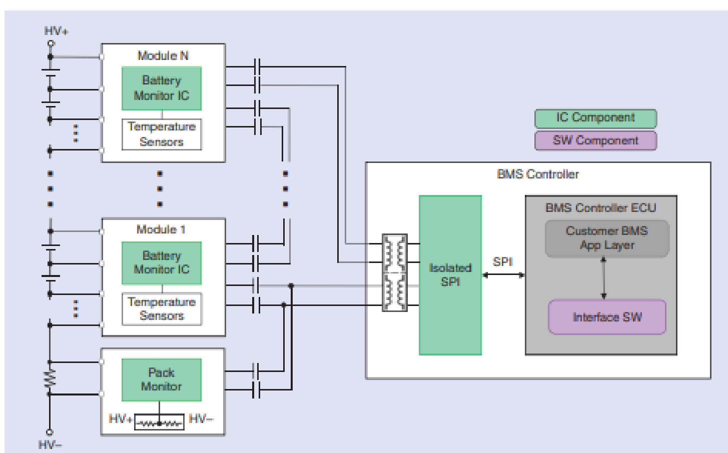


Figure 4: Example of a wired BMS system

1.4 Wireless technologies proposed for a WBMS

1.4.1 ZigBee/ZigBee Pro

This communication protocol allows the creation of a low rate wireless personal area network (WPAN) based on the ISM band allocated at 2.4 GHz, but it also uses the band allocated between 800-900 MHz. The data rate at 800-900 MHz is limited at 20kbps, while at 2.4 GHz arrives at 250 kbps. The frequency band is divided in 16 channels, spaced by 2 MHz using the 800-900 MHz band, while the spacing is of 5 MHz at the 2.4 GHz band. ZigBee is intended to support a number of network topologies such as mesh, star or tree thereby supporting a high transmission range. An improvement in the protocol is represented by ZigBee Pro that allows to support an higher number of nodes and it is studied to bee a low power communication method, especially for infrequent communications and for allowing long battery life and transmission of small data packets. The structure of the protocol is very simple: it is made up of four layers, two of them at physical level (Physical layer and Link Layer) and the remaining at Alliance level (Network Level and Application Layer). The type of protocol used is Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA).

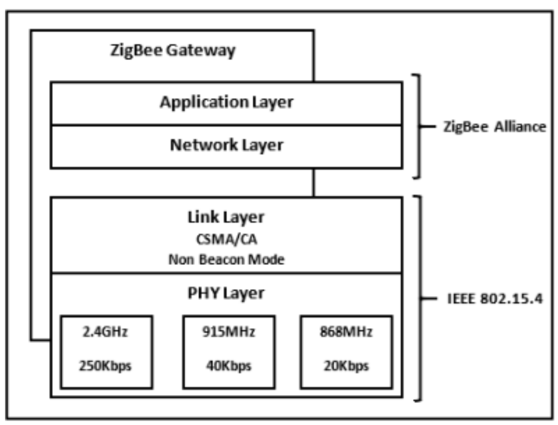


Figure 5: ZigBee/ZigBee protocol structure

1.4.2 Bluetooth Low Energy (BLE 5.0)

This communication technology is well known since it has been used and developed initially for smartphone and cellular applications and over the last five years it has started to be of interest also for the automotive world. It is particularly attractive for the automotive environment since is able to maintain ad-hoc connections limiting the power consumption. Bluetooth operates in the 2.4 GHz ISM band and allows a maximum data rate of 1 Mbps. It uses three advertising channels to search for other devices and activates for 0.6 to 1.2 ms. After connection, it utilizes the Adaptive Frequency Hopping in a pseudo-random manner, so to avoid interference.

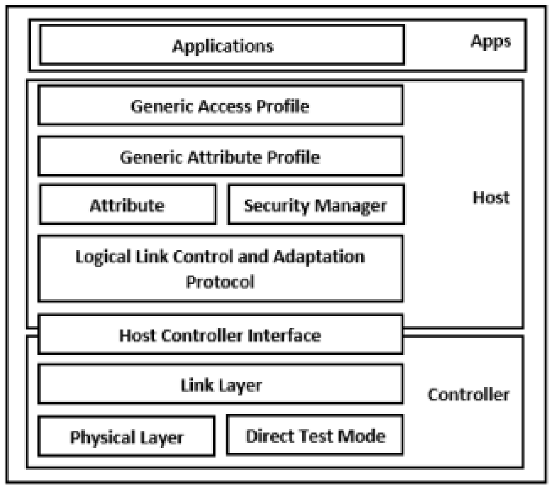


Figure 6: Bluetooth 5.0 LE structure

1.4.3 Wi-Fi(IEEE 802.11)/Wi-Fi HaLow(IEEE 802.11 ah)

Among the previous communication protocols, Wi-Fi for sure is the one that provides the highest communication range and data rate, but at a price of an higher power consumption. IEEE 802.11 protocol operates at the unlicensed ISM band at 2.4 GHz and at 5 GHz. Wi-Fi HaLow was introduced with an amendment and offers longer range with a lower power consumption, supporting up to 8192 devices. It operates in the sub-Gigaherzt unlicensed ISM band at 900 MHz. The power consumption is reduced thanks to mesh network topology and since it is based on the existing Wi-Fi standard, it supports IP protocol at the node. It can support a data rate of 347 Mbps with 4 spatial streams using a transmission channel with a width of 16 MHz, or it can support a data rate of 650 kbps with a channel width of 2 MHz. At the moment, there are no chipset using Wi-Fi HaLow available on the market, but companies involved in the Wi-Fi Alliance are working on developing chip sets.

1.4.4 Near Field Communication

Unlike the previous communication systems that are based on the usage of electric fields, NFC technology uses magnetic field and this makes connections of devices possible within few fractions of second. Devices using NFC technology can remain no power consumption state until a transmission is executed. NFC technology has gained acceptance in the automotive field due to its ability to avoid "man in the middle" attacks. Anyway, it is affected by an important limitation: the very short range of communication, compared with other communication protocols. NFC devices operates using the unlicensed free ISM band at 13.56 MHz and offers a maximum bit rate of 424 kbps.

1.5 Performance indicators

1.5.1 Range

The range of transmission of communication protocols depends on many aspects: it's proportional to the output power of the transmitter, depends on the RF sensitivity measured in dBm. It is also highly dependent on the environment where the transmission happens, especially if it is highly congested with other electronic devices that can create electromagnetic interferences, it depends also on the carrier frequency and on the layout and coding scheme.

Communication Protocol	Range[a]
Zigbee	100m
BLE5.0	100m
Wi-Fi(IEEE 802.11)	150m
Wi-Fi HaLow	1000m
Near Field Communication	10cm

Figure 7: Ranges of communication of the proposed protocols for developing a WBMS

In a WBMS environment, which is particularly hostile due to the co-existence of several electronic devices that can create electromagnetic interference, these numbers are not precise. Also the placement layout of the MVu and CMBU will greatly impact such values. For a MCU communicating with CMBU installed in a distributed way BLE 5.0 is the most appropriate choice due to its optimum range and the ability to provide an ad-hoc support to then Piconet. Unfortunately, the most important limitation is represented to the limited number of slaves that can be supported within the Piconet, which is 7. ZigBee technology will find its use in a distributed architecture here the inter-CMBU communication will be facilitated along with the communication to MCU, since a single master can support up to 65000 slaves. Near Field Communication can be used within an integrated architecture where the range of communication is particularly short. Wi-Fi protocol, though providing a considerable range, will be disadvantageous due to its peculiar power consumption. Wi-Fi HaLow can be used an optimum alternative to Wi-Fi with an efficient power consumption characteristics for a higher range.

1.5.2 Power Consumption

An important factor that can also determine the choice among the different protocols proposed and that also drives the switch from wired to wireless solutions is the power consumption. Respect wired solution, the wireless one can be easily powered even by a button-coin battery, like the ones used for clocks. ZigBee protocol operates with a very low duty cycle (¡ 1 %) so to optimize the usage of the power, BLE 5.0 manages the Piconet so to optimally reduce the power consumption of each device connected, Wi-Fi, as its known, is designed not looking at the power reduction but looking at high rate of transmission, Wi-Fi HaLow is the optimized version of Wi-Fi and uses the concept of ultra low duty cycle like its counterparts to minimize power consumption and implements power saving mode where the station alternates between Awake state(can transmit and receive signal) and Doze state (turns off the radio components). So, for this voice, ZigBee, BLE 5.0 and Wi-Fi HaLow are the most promising protocols. NFC for sure is the most efficient in terms of power consumption but its transmission range is very small.

1.5.3 Communication range

The communication range depends on three main aspects: frequency of the carrier, modulation scheme and packet lengths. The communication range deeply affects the power consumption and the amount of bandwidth utilized. Wi-Fi (IEEE 802.11) offers a raw data rate of 11 Mbp while the wi-Fi Halow offers an improved data rate of 347 Mbps. These two protocols, for the WBMS applications, are overspecified. Instead, ZigBee and BLE 5.0 with the respective values of 250 kbps and 1 Mbps are the ideal choice for implementing a WBMS system.. As said, these numbers represents raw data rate and this because inside a packet there are not only the useful data but there are also info like the receiver and transmitter IDs, the checksum and the header which represent the not useful part of the packet. An inefficient protocol spends considerable energy in transmitting non-useful data thereby reducing the throughput of a particular technology.

Communication Protocol	Raw Data Rate	Payload throughput
Zigbee	250 Kbps	200 Kbps
BLE5.0	1 Mbps	305 Kbps
Wi-Fi(IEEE 802.11)	11 Mbps	6 Mbps
Wi-Fi HaLow	720 Kbps	650 Kbps
Near Field Communication	424 Kbps	106 Kbps

Figure 8: Confront between raw and actual data rate of different protocols

1.5.4 Latency

The latency is the delay between the transmission of a data packet and its reception. Usually, to reduce the power consumption, when a device is not transmitting anything goes in sleep state, shutting down the RF circuit. But then, when a transmission must be done the time needed to weak up the RF circuit, and so the device, deeply impacts on the latency of the communication. In BLE and Wi-Fi Halow devices need something like 3 ms to weak up, in NFC less than 1 ms, while in ZigBee 30 ms are necessary.

1.5.5 RF Co-Existance

Almost all of these communication protocols uses the same Industrial, Scientific and Medical(ISM) unlicensed frequency band, increasing the probability of interference from each other if a multitude of objects are setup in the same geographical area. This leads to increase in error packet rates or failure of communication altogether and in turn influence the power efficiency.

In Electric Vehicle application, a number of Electronic Control Units are in mutual existence that may run on different protocols. So, the implementation of interference reducing techniques is required for the communication to happen successfully and accurately. BLE5.0 and ZigBee implements spread spectrum techniques, Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) respectively to assist co-existence. FHSS uses pseudo random sequence generator to derive the transmission frequency while in DSSS the signal directly is combined with pseudo random sequence at the transmitter end and then extracted at the receiver. Wi-Fi uses a complex combination of DSSS with Orthogonal Frequency Division Multiplexing (OFDM) in which the modulation carriers are transmitted orthogonally to minimize interference. Near Field Communication is immune to interference due to its short range of communication but there may be disturbance due to an FM receiver located in vicinity.

1.5.6 Hardware Implementation Feasibility

One of the most important factor on switching from wired to wireless is the significant reduction in design and implementation costs. In wired solution conventional system requires the usage of number of components like modules, isolator for providing isolation between High Voltage and Low Voltage lines, Isolated CAN or Isolated SPI transmitter for communication between MCU and CMBU. Moreover, the design of such networks requires also important respect of clearances and creepage distances.
In wireless communication system the means of communication is air which is already an isolator and so what is only needed is the protocol relevant chipset and planar antenna which can be implemented on the chipset itself. The type and design of the antenna is driven on the transmission frequency of the chosen protocol.Also, factors like placement of Battery Monitoring and Control

Units, housing materials in the battery box will dictate antenna parameters like impedance, sensitivity and antenna factor.

1.5.7 Benefits of a wireless BMS over a wired one

The benefits offered by a wireless BMS over a wired one are the following:

- Higher flexibility of the system in terms of scalability and installation, since the same hardware can be easily adapted on several types of electric and hybrid vehicles, unlike the wired system

- The wireless system brings with it the advantage of a reduction of the overall weight due to the absence of kilometers of cables

- The absence of cables brings also an easier installation of the overall system

- The wireless BMS allows to perform remote monitoring of the battery state

- Balancing high and low voltage: BMS is a product that connects high and low voltage. As in electric vehicles, most ECUs are out of the low voltage system, while the BMS is a module connecting high and low voltage, so the primary consideration in BMS design is how to effectively isolate the high voltage and low voltage units, and reduce the interference of the high voltage system on the low voltage system. The use of wireless communication can naturally isolate the high-voltage unit from the low-voltage unit.

Anyway, along with the advantages, there are also the disadvantages in using a wireless BMS and they are the following:

- Higher initial investments respect a wired BMS system, due to the need of a wireless communication network

- The wireless communication can also bring with it an improved risk of data loss due to potential signal interferences or problems

- The presence of environmental interference can lead to potential problems of data loss and so can affect the quality and reliability of the transmission

- Unlike wired BMS through physical connections, wireless BMS without the implementation of proper encryption and authentication measures poses a potential cybersecurity risk, leaving the system vulnerable to unauthorized access or data leakage.

1.5.8 Conclusions

In conclusion of this overview among the five main wireless communication technologies that can be used in automotive environment, for implementing a wireless BMS the best candidates in terms of range, data rate, delay and security are Bluetooth LE 5.0 and WiFi-HaLow. Anyway, among these two protocols, the one to choose is the BLE 5.0 since is a technology that over the last 5 years has started to make its gradual introduction within the automotive world, and chipsets are already available over the market, unlike Wi-Fi HaLow.

2 Energy storage devices used onboard EVs

2.1 Different types of electrochemical energy storage devices

Electrochemical devices that can be used on board EVs can be classified in different types depending on their chemistry, the way in which they store energy and also on parameters like the energy density and the power density. Fuel cells are able to provide high values of energy and power density but their development and application in the automotive sector is relatively slow, mainly due to problem related on the hydrogen storage. Devices like ultra and super capacitors are characterized by an high value of power density and a relatively low value of energy density so, they cannot be used for supporting long range travels, they are used only when it's necessary to have a boost of power for very short transients, like when accelerating. Batteries instead are mainly characterized by high values of energy density and relatively low or moderate values of power density. These characteristics make them appropriate for supporting long range travels and so to act as main energy storage devices for EVs. At different stages, the main characters in the wrold of batteries for automotive application can be found lead acid batteries and nickel-based batteries, in particular LIBs. LIBs can be regarded as an important advance in battery technology due to their superior KPIs, especially in terms of energy density, ling cycle life and high safety. LIBs are able to operate within a window of relatively high temperatures, around 270 - 400 °C. Metal/air based batteries are differentiated between them looking at the metal that is present at the anode, which can be lithium or zinc. Generally these batteries are characterized by having high energy densities but a relatively low cycling life.

Flow batteries, from the working point of view, are closer to fuel cells, rather than conventional batteries. Other technologies like aluminum-ion, zinc-ion and magnesium-ion are still under research and development, anyway their market entrance will happen much sooner than expected in the past. In the past, lead–acid batteries are only used as "starter batteries" and are not intended to power cars for long driving ranges. In recent years, LIBs have gradually replaced the lead–acid and nickel-based batteries and will dominate the EV market for powering our transportation in the next decade.

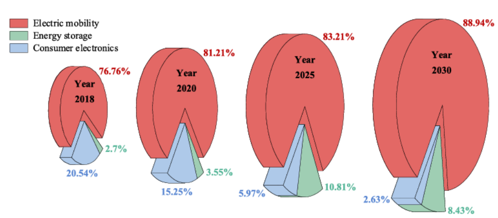


Figure 9: Demands of batteries by application

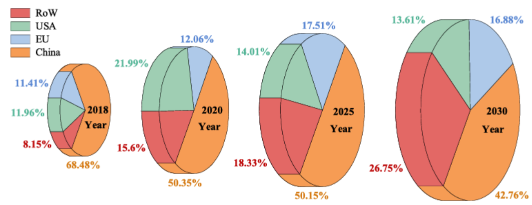


Figure 10: Demands of batteries at different regions

2.2 State of the art of batteries

LIBs, as said in the previous section, are characterized by having high values of energy density and moderate values of power density. These batteries, from the internal structure point of view, are characterized by anode, cathode and separator. This last component is necessary to not put in direct electric contact the two electrodes and also is used to properly discriminate the flow of ions within the cell. Electrons, instead, are driven through the external electric circuit.

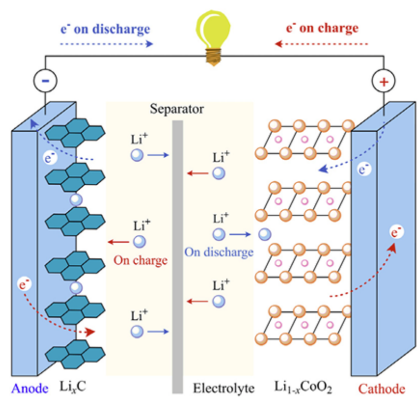


Figure 11: Working scheme of a LIB cell

The lithium-ion batteries started to be gradually commercialized from 1992, by Sony, while two types of primary batteries based on Zinc Manganese dioxide and lithium metal system were developed back in 1866s and 1960s.

Before the popularization of lithium batteries, two candidates of lead-acid battery and nickel-based battery were developed respectively in 1859 and 1899. Rechargeable lithium acid batteries are well known in the automotive sector and they are mainly used for lighting, ignition and for starting. They are characterized by low energy density and low specific energy (40 Wh/kg and 90 Wh/l at cell level). Instead, state of the art LIBs are characterized by high values of energy density and specific energy (260 Wh/kg and 700 Wh/l at cell level).

Ni-Zn batteries represent a new technology, represented by high specific energy and low material cost, but its drawback of short cycle life limits the commercialization.

- **(1) Lead-Acid Batteries** They dominated the automotive market for over a century due to their low cost, reliability and maturity of the technology. Typically, the valve regulated lead acid battery (VLRA) has attained important advancements in terms of specific energy, specified power and recharging speed, making them more suitable for automotive applications. Bipolar VLRA and UltraBattery are at the moment the most promising lead-acid batteries.

- **(2) Nickel-based Batteries** In nickel based batteries the cathode is always characterized by nickel oxyhydroxide and they differ on the material used at the anode, so it is possible to have nickel-iron (Ni-Fe), nickel-cadmium (Ni-Co), nickel-hydrogen (Ni-H_2). The Ni-Zn battery are characterized by having the highest cell voltage among the one above (1.6 V). Ni-Zn are more environmentally friendly than Ni-Co and are also able to achieve higher specific energy. They also have higher tolerances on over-charge and over-discharge.
  Due to the solubility of zinc species in the electrolyte, Ni-Zn suffers from a short cycle life of around 300 cycles and this severely limits the commercialization.
  Ni-MH battery has been well accepted by the EV market since 1992. The nominal voltage is 1.32 V and the specific energy is higher than the one of lead acid battery.

2.3 Lithium based batteries

Lithium-based batteries opened a new season, a new era for the high-energy and high-power batteries and more and more replace other battery technologies, such as lead-acid and nickel-based systems.From the late 1960s many battery technologies have been explored and this because the aqueous batteries failed on satisfying the booming demands for portable energy storage.

2.3.1 Lithium-Metal Batteries

The very first experimentation on lithium based batteries are dated back in 1912 by G.N Lewis, so many years before the first experimentation on lithium-ion batteries of 1976. LMBs typically use the metallic lithium as anode material and also as non-aqueous electrolyte. They immediately represented a breakthrough technology due to their higher specific energy and high energy density. The development of primary lithium based batteries pushed the researches and development of secondary lithium-metal batteries. In particular, the focus was on finding an appropriate cathode material and researches were conducted by Wittingham between 1976 and 2004. Unfortunately, at the moment, rechargeable

LMBs present an important safety issues, which make them hard to commercialize.

Nevertheless, the Li metal has the advantage iof having a very high capacity, of 3860 mAh/g and lowest operational potential of -3.04 V. The LMBs are candidates for EV propulsion thanks to their considerable high energy density and specific energy and capacity. Even though there are various types of LMBs, like LSBs and lithium oxygen batteries, which are typically based on a lithium metal anode and layered oxide cathode in combination with a solid electrolyte. SSBs are seen as the most promising technology to further boost the energy density for EV application.

2.3.2 Lithium-Ion Batteries

In the 80's Goodenough and its collaborators opened a new era for LIBs for power applications. The story of lithium-ion batteries can be divided into three frames: commercialization since 1991, exploration since 2008 and foresight since 2019. The 1st generation of LIBs was based on $LiCoO_2$ as cathode material and petroleum coke as anode material. From 2nd and 3rd generation, improvements have been done over the anode material and the electrolyte, passing from hard carbon to graphite. These evolutions brought an improvement in energy density of LIBs. The state of the art LIBs, for high energy applications, use a layered lithium nickel cobalt manganese oxide layered cathode ($Li[Ni_xCo_yMn_z]O_2$) thanks to their improved capacity and reduced cost respect $LiCoO_2$.

Energy density of LIBs can be further improved by increasing the amount of nickel content inside the layered cathode and also by adding silicon to the graphite negative electrode. In fact, today NMC622 ($Li[Ni_{0.6}Co_{0.2}Mn_{0.2}]O_2$) and NMC811 ($Li[Ni_{0.8}Co_{0.1}Mn_{0.1}]O_2$) can be considered as the state of the art cathode materials for automotive applications. For what concerns the anode, graphite is still the dominant material and only few cell apply also silicon. In recent years, several batteries have started to use a blend of NMC and LMO ($LiMn_2O_4$) for regulating the energy/power ratio. At the same time $LiFePO_4$ based LIBs have started to become very popular in the automotive environment, despite their lower energy density, due to a consistent safety, high cycle life and low cost. LIBs have successfully improved their specific energy, from only 98 Wh/kg of 1990 to 195 Wh/kg of 2008 and more today. Another alternative of LIBs that is making its advent inside the automotive industry, especially where fast charging is required, like for electric busses, are the ones using a spinel of $Li_4Ti_5O_12$ at the anode. Anyway, this alternative does not present an high value of energy density and capacity, but at the moment are seen as potential alternatives for the future.

The popularization of EVs will express an increasing requirement on batteries' KPIs, especially energy density, fast charging and safety, which will generate a powerful motivation to search for novel materials for LIBs and to look for advanced technologies beyond lithium.

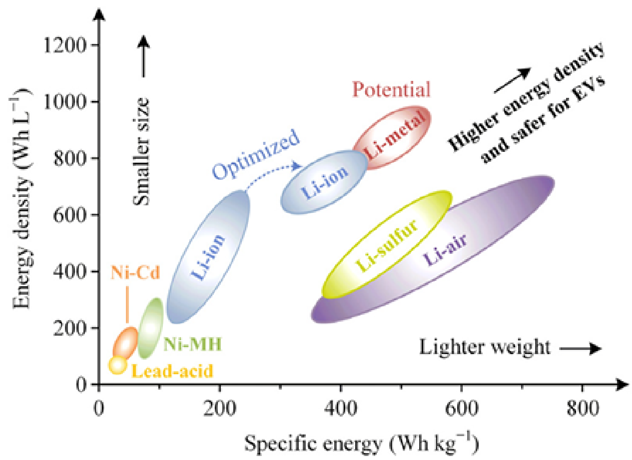


Figure 12: Energy density and specific energy of different types of cells

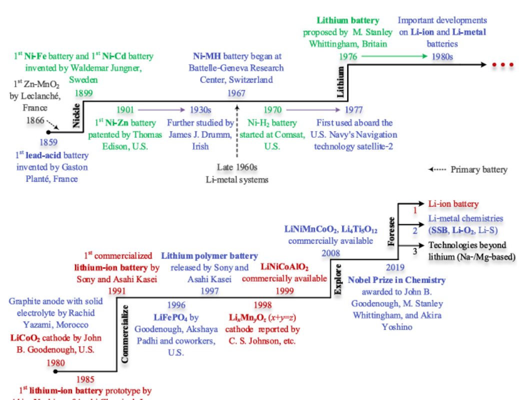


Figure 13: Hystoric evolution of battery cells

2.4 Battery technologies beyond lithium

Lithium-Ion cells are the state of the art technology at the moment and are inevitably reaching their intrinsic limits on specific energy and energy density. For this reason, since last decade, many studies have been conducted on technologies that are considered alternative to lithium. The main alternative, at the current state of the art are: metal/air batteries, sodium-beta batteries and other alternatives that are going to be depicted below in the following sub-paragraphs.

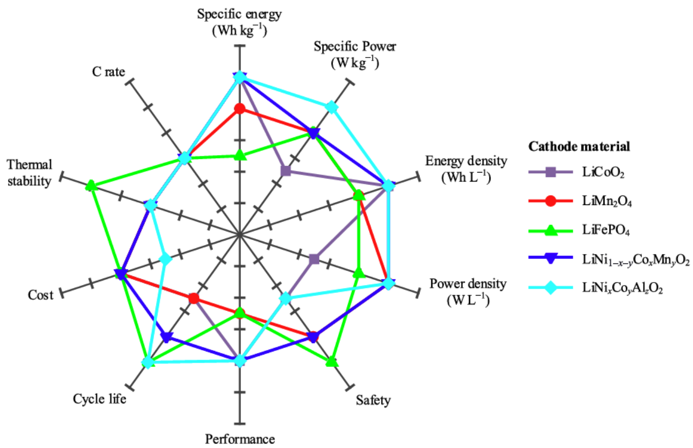


Figure 14: Comparison for different anode materials

2.4.1 Metal/Air Batteries

These cells are characterized by having the metal at the anode and the air cathode. Obviously, the type of metal that constitutes the anode deeply affects the specific energy and the energy density of the cell. The values of energy density and specific energy offered are high and are typically around 600 Wh/kg and 400 Wh/l. The different type of metals that can be used at the anode are: zinc, aluminum, iron, magnesium, calcium. they can be manufactured as primary batteries or even as rechargeable, both electrically and mechanically. The main drawback of these rechargeable batteries are the alkaline carbonization of the electrolytes and the low specific power.

2.4.2 Sodium-Beta Batteries

Sodium-beta batteries are renowned for their high specific energy, and the main two technologies that are currently being commercialized are sodium/metal chloride (Na/MCl_2) and sodium/sulfur (Na/S). To provide good ionic conductivity, these batteries must be operated at a temperature within the range of 270 ° C - 350 ° C.

- The cathode material of Na/MCl_2 adopts the transition metal chloride. generally the two most used alternatives are iron and nickle chloride, but the former has got more development than the latter. Recently $Na/NiCl_2$ battery has the advantage of wider operating temperatures, less metallic corrosion and higher power density.

- Na/S cells adopt the sodium at anode, the sulfur at cathode and use beta-alumina as ceramic electrolyte. Sodium pentasulfide is generated from the reaction of the sulfur anode and sodium ion. The performance of Na/s

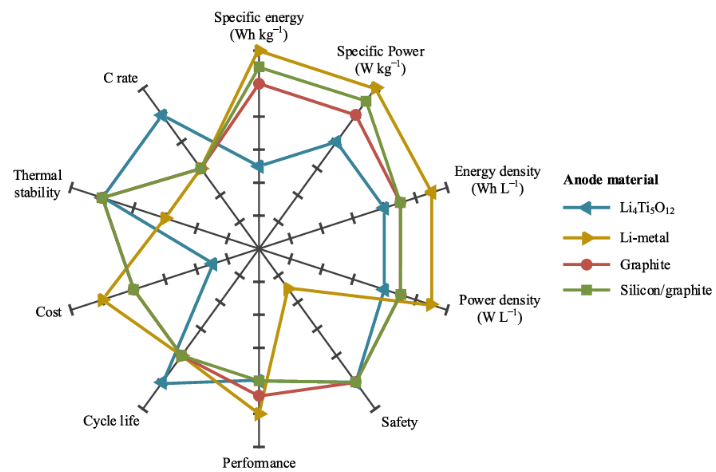


Figure 15: Comparison for different cathode materials

battery degrades with the increasing internal resistance, which is worsened with the incremental deep of discharge. Recently, room-temperature Na/s battery have been explored with high capacity and stable cycling performance.

2.4.3 Alternative Batteries

Other alternatives to Lithium-Ion and Lithium/metal are related to metals like zinc (Zn), sodium (Na) and magnesium (Mg).

- SIB has attracted intensive investigations since 2010, and numerous anode and cathode materials have been discovered. Generally, these batteries offer energy densities around 163 Wh/kg and 210 Wh/kg which are slightly lower respect the one offered by the high energy LIBs. Nevertheless, SIBs represent a good alternative to LIBs since sodium is widely spread on the earth surface and its chemistry is quite similar to lithium. The SIBs KPIs can be improved by choosing the electrolyte materials, such as carbonaceous materials and inter-metallic and organic compounds for anode materials. Both the cell design and the electrode balancing challenge the further development of SIB.

- Zinc-ion batteries recently have been under the focus of researches. The mild aqueous electrolyte endowed the ZIB with a new vitality in energy storage system and portable electronics. Acceptable energy density and intrinsic advantages on safety and environment are provided. Very recently ZIBs have started to adopt MnO_2 as cathode material. The Zn-MnO_2 are recognized as promising alternatives for large scale static energy storage systems. New proposed alternatives are able to reach a cell voltage of 1.95 V, with a gravimetric capacity of 570 mAh/g and an energy density of around 409 Wh/g.Another secondary Zn–Mn battery with near-neutral electrolytes was developed by using highly active Mn_3O_4 carbon nanowires,which showed superior performance in reversibility, capacity,and cycling durability.

- Due to the low cost, superior safety and environmental friendliness, magnesium-ion battery (MIB) was believed as an alternative to LIBs by some researches, especially for stationary and mobile energy storage. Magnesium is more abundant than lithium, since it covers 2.3 wt % of Earth's crust. An iron chalcogenide (FeS_2) nanomaterial cathode enhanced the reversible capacity for the MIB with a copper current collector.

2.5 Battery cells used in this thesis project

The cells that have been installed for developing the 3s3p battery and the 13s3p, which are used in the following thesis project, are the SAMSUNG 21700-50G.

They are lithium-ion cells with a an NMC 811 [$Li(Ni_{0.84}Co_{0.10}Mn_{0.06})O_2$] + 1 % wt Si, formulation for the cathode and a graphite SiO_x anode. These cells are a very good choice whenever it is necessary to have high energy sources for developing devices like electric scooter, electric bikes or powerful light torches.

In terms of energy density they offer 267 Wh/kg, which in term of volumetric energy becomes equal to 740 Wh/litre. Instead, in terms of specific power they offer 1176 W/kg which is equivalent to 3261 W/litre.

They are cylindrical shaped with a flat-top architecture and the dimensions are the following: height of 70,15 mm for a diameter of 21,10 mm. A single cell has a mass of 0,068 kg +/-0,001 kg They are characterized with a charging voltage of 4,2 V and a nominal voltage of 3,63 V. The standard discharge capacity is of 4900 mAh and rated discharge capacity is of 4753 mAh. The standard charging current is of 1617 mA with a 0.33 C charging and maximum charging current is of 4900 mA (1C). The standard charging time is of 4 hours.

The maximum charging current is of 4900 mA for continuous discharge while of 14700 mA for non continuous discharge. The charging method which is used is CC-CV.
The discharge cut-off voltage is of 2,5 V. The cell maximum weight is of 69,5 g.

For what concerns the environmental conditions in which this battery has to work, generally the operating temperatures for charging are from 0 to 45 °C, while for discharge can go from -20 °C to +60 °C.

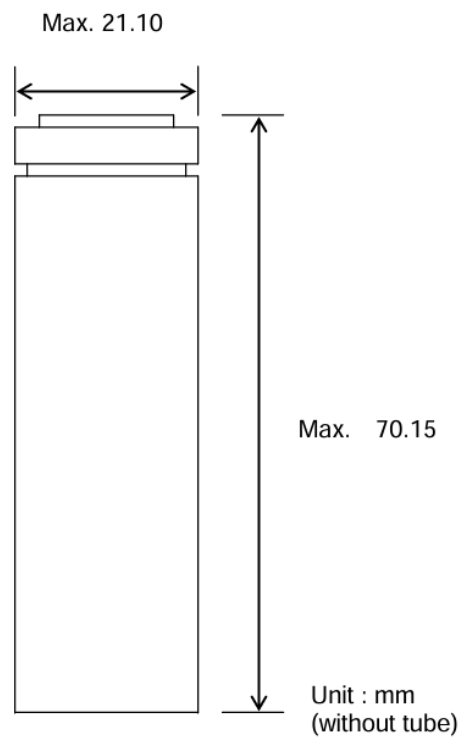


Figure 16: SAMSUNG INR21700-50G

2.6 The 3s3p battery pack

The battery pack that has been developed and that will be manufactured and tested for future applications is the 3s3p, which means that it is made up by nine cells connected in this way: 3 series of 3 cells connected in parallel with each other.

The battery has been developed from scratch, in every single aspect, from the electrical connections of the cells to the components of the pack that have been designed and tested in SolidWorks environment. The design process has been driven by different voices: packaging reduction, safety, efficiency of the connections and efficient cooling.

The packaging reduction has been achieved by installing the nine cells close to each others, leaving only 2 mm, in the closest point, between two adjacent cells. Obviously, the main risk on installing cells very close to each others is represented by accidental contact between positive and negative which could lead to a potential short circuit. To avoid this from happening, a divider is necessary to be used, which allows to space each cell from the next one, putting a layer of resistive material, which is PLA. So, the divider helps also on achieving also the safety requirement. In terms of design, the divider it's just a plate with a thickness of 5 mm with holes of the diameter of 21,10 mm + 1 mm of tolerance.

For what concerns the connections, the idea is to connect each cell by using Nickel strips which are welded by using an electric arch welder. Obviously, the series connections are achieved by connecting the negative of the previous cell with the positive of the subsequent one, while the parallel connections are done by welding the nickel strips between the positives of two adjacent cells.

For achieving the last requirement, the efficient cooling, the idea is to install the whole battery pack within a casing, by using a busbar mount which offers the support base to the 3s3p and also offers the passage for the power cables that will come out from the casing, so to allow the whole pack to be easily connected to an external load. As can be seen from the picture below, the cells running from top to bottom are connected in series, so the nickel strip is first welded on the negative of the far-most cell and then gets welded to the positive of the next one, and so on until the last cell; instead running from left to right parallel connections have been established, connecting the positives between each others.

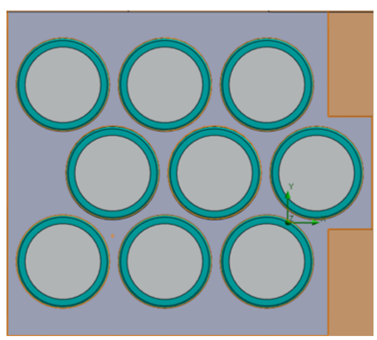


Figure 17: 3s3p model seen from above

2.6.1 Top and bottom cooling - casing

Among the different requirements that have driven the design process of the 3s3p battery pack, the one that has had a major impact on many choices, especially for the development of the casing and dividers is the cooling.

From previous experimental tests that have been exploited on the used cells, has been noticed how the lower part is the one that heats the most, together also with the top, simply because these are the spots where there are the nickel strips conducting the current. So, together with the thermal emission of the cells while charging or discharging, there's also the additional emission of heat due to Joule effect. So, one of the main goals has been to design a casing that allows to perfectly split the fluid flow at the inlet in two equal flows, impacting with the top and bottom of the cells, providing an homogeneous cooling of such areas.

The base design of the casing is obtained from a previously one existing, that was developed for a previous thesis project, always based on a 3s3p. So, as requested while designing, the external dimensions and volume of the new casing are the same of the base one, what has been deeply changed is the internal volume, that has been completely re-designed by doing the following actions:

- **Introduction of the fluid splitter** at the inlet, for properly splitting the fluid at the top and bottom. The splitter is simply a box directly embedded inside the casing with an inner channel that divides into two channels allowing the fluid to be homogeneously distributed between top and bottom, without any recirculation, vortex generation or impingement.

- **Concave shaped outlet** for properly guiding the flow of fluid outside the casing, without creating vortexes, leading the leaving mass flow rate being the same of the one at the inlet.

- **Improved internal volume** for leading the fluid to properly develop and flow through the cells, without recirculating or impinging.

- **Changed position of inlet and outlet**: in the baseline configuration, inlet and outlet were placed at the bottom, because the casing was develop for hosting a battery that needed to be tested at with different level of fluid filling: 25 %, 50 %, 75 % and 100 %. This is also the reason why the internal walls show the presence of gaps: these gaps are used as a reference for installing the fluid divider and imposing the filling level that needs to be tested and this is a feature that is present even in the re-designed casing.

- **Added apertures at the bottom** for letting power cables coming out from the casing, so to connect the battery to an external load.

- **Rounded top surfaces** for hosting a new lead with a more aerodynamical inner design, that helps the fluid flowing at the top to circulate without any impingement.

- **M3 threaded holes** for screwing the lid to the casing make it tight from leakages.

As can be seen from the pictures below, the casing has been completely re-designed both externally and internally and another important difference is also represented by the thickness of the inner walls, which in the newer version has been doubled, from 3 mm to 6 mm for hosting the threaded holes for the M3 screws that are used for closing the lid on top the casing.

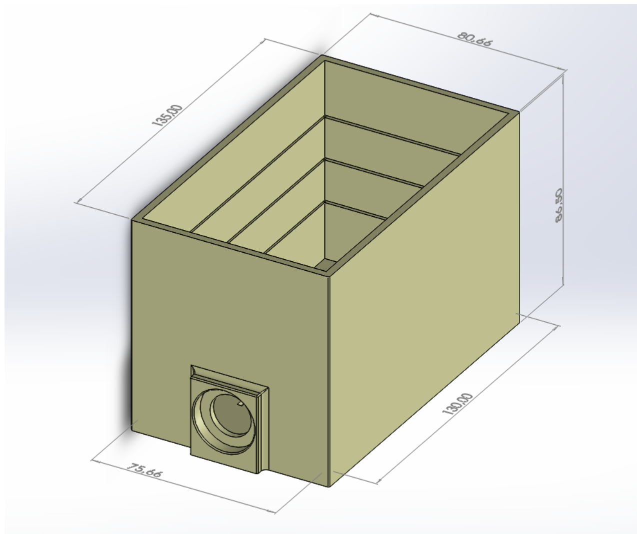


Figure 18: Baseline casing

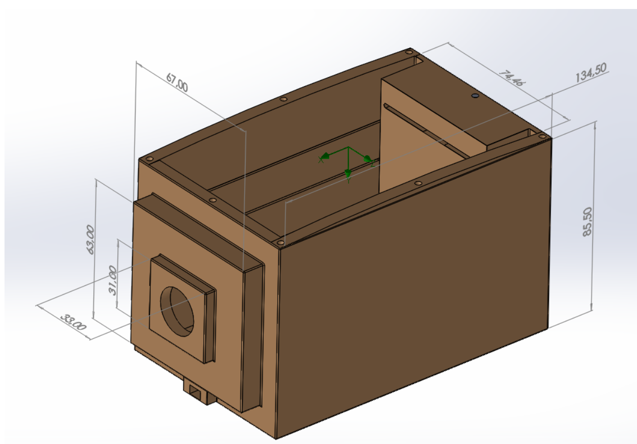


Figure 19: New casing with top and bottom fluid splitter

2.6.2 Top and bottom cooling - what's inside the casing

The design of the inner volume of the casing is the result of many different CFD simulations run in SolidWorks environment, through which it has been possible to properly refine the shapes of the inlet, outlet and of the fluid divider. Such simulations are going to be discussed in a specific chapter of this thesis. Instead, in this subparagraph a look to what's inside the casing is given. As can be seen, the components inside the casing are mainly three:

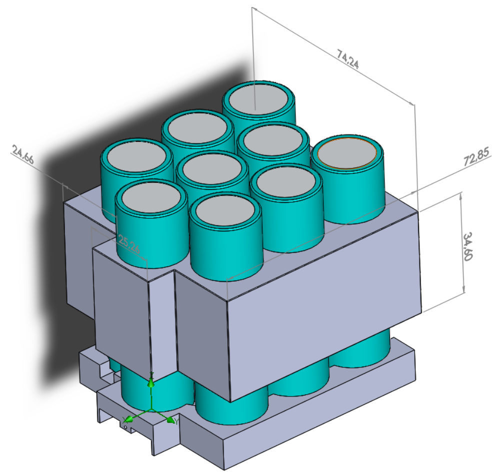


Figure 20: 3s3p battery pack fully assembled for top and bottom cooling

- **The nine cells** creating the 3s3p battery. Even if in the CAD model are not present, on bottom the nickel strips are going to be welded, creating the electrical connections that make work the battery.

- **Central fluid divider**: it is the component developed for spacing the cells in a safe way, avoiding them from accidentally touching and creating a short circuit and at the same time it guides and confines the fluid flow at top and bottom of the cells.

- **Busbar mount**: it is the component at the bottom that supports the nine cells and allows the entire pack to be hosted within the casing. The bus bar also presents the space necessary for hosting the power connections and the power cables and below the cell modules measuring voltage, current and temperature are going to be installed.

2.6.3 Central cooling

During the development of the first casing, has been also requested to design a second one which will be used for testing the behavior of the battery pack when it gets cooled only at the center.

This new requirement has lead to a deep change at the inlet, in fact the fluid splitter has been completely redesigned and instead of having two slots at the top and bottom it has only a circular aperture at the middle and inside there's a divergent channel that has the main goal to help the fluid flow developing and stabilizing.

In particular, the channel inside the fluid splitter has been refined through several CFD simulations, since with the first versions generation of vortexes and recirculation of fluid has soon as it impacted with the first row of cells was noticed. So,it was necessary to develop first a divergent channel which helps the fluid flow developing and then straight channel that helps stabilizing the fluid, so that has it impacts the cells follows the shape of the lateral surfaces and acts efficiently.

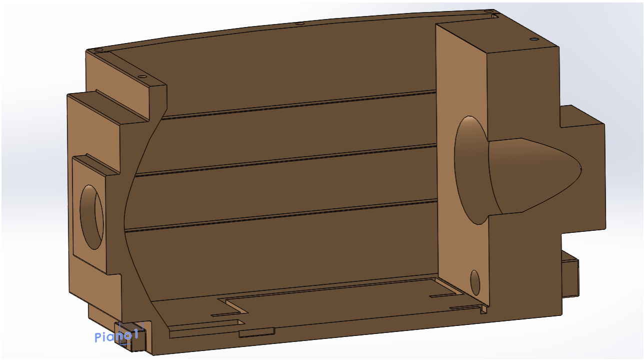


Figure 21: Central cooling casing - lateral section

In terms of dimensions nothing changes, both internally and externally. Instead, for what concerns what's inside the casing what changes is that instead of having a single central fluid divider, this time there are two, thinner, positioned on top and bottom, both of them covering 25% of the height of the cell, so to leave 50% of height free, so that the fluid can pass and cool the central body of the cells.

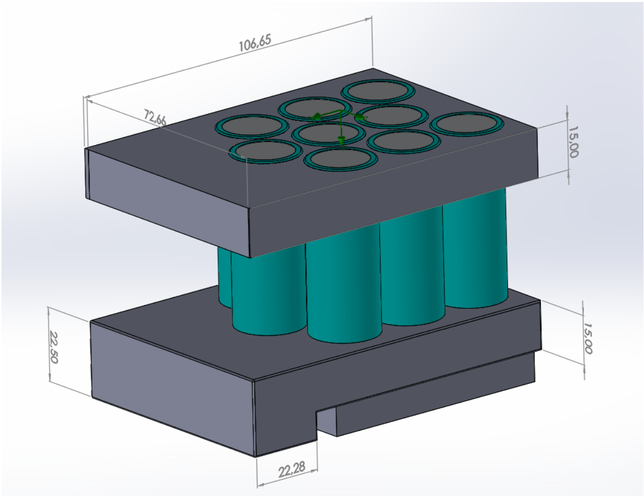


Figure 22: 3s3p fully assembled for central cooling

2.7 13s4p battery pack

The 3s3p battery pack is not the only one considered in the following thesis project, in fact as said, this is a pack that has been designed from scratch and developed in virtual environment and that now needs to be manufactured and assembled for future tests and studies. Meanwhile this pack has been designed, another pack has been already manufactured and assembled and this is a 13s4p Li-ion, designed for providing 46,8 V and a capacity of 19,6 Ah

The components characterizing this battery pack are the following:

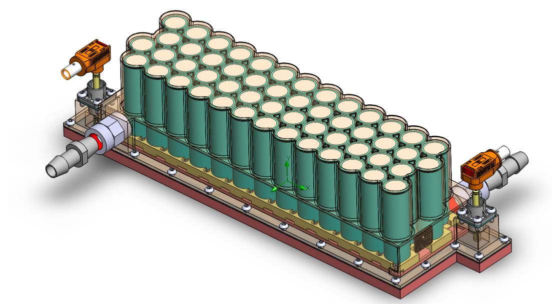


Figure 23: 13s4p battery pack fully assembled - CAD model

- **Casing**: in the CAD representation it is transparent, but it is literally a component made by two parts, both 3D printed in PLA: main body that covers the whole length of the cell and the busbar mount; the base that has the main goal to close the pack and is connected to the main body using M4 threaded screws.
- **Inlet and outlet connectors**: used for connecting the battery pack to an external liquid based cooling system. The inlet is positioned slightly above the outlet.
- **Power cables connectors -three ways valves**: these are the orange components that can be seen close to the inlet and outlet connectors. Here are attached the positive and negative terminals of the whole battery pack and through them it is possible to connect the battery to an external load.
- **Busbar mount**: The busbar mount, like in the 3s3p case, has the goal of sustaining the cells within the pack, giving to them a base support and then provides enough space for hosting the power connections between the cells.
- **Future development - SEEED XIAO ESP32C3 BLE transceiver**: It is the master board of the Bluetooth 5.0 LE based wireless BMS system and it is installed inside the casing, in a lateral face, as it is visible from

the picture above. The slave boards are going to be installed underneath the busbar mount, so to monitor each single parallel.

- **EMUS G1 cell modules**: even if in the CAD representation they are not shown, underneath the busbar mount are going to be installed the EMUS G1 cell modules which, in the wired BMS solution, are the boards responsible for measuring the voltage and internal temperature of each parallel. The busbar mount not only provides enough space for installing the cell modules, but it also allows the passage of communication cables that are necessary for letting all cell modules talking with each others and then communicating with the central BMS.

- **SAMSUNG 21700-50G cells**: the 52 cells are arranged in this way: the battery is made up by 13 series and each single series is characterized by 4 cells connected in parallel. This configuration leads the battery pack reaching a voltage of 46.8 V and a capacity of 19,6 Ah.

- **EMUS G1 Control Unit**: it is not visible in the CAD model and neither in the picture below, but it will be shown in the next chapter, where the connection to the wired BMS will be discussed. The BMS will remain external to the battery pack and will be connected to it through optical isolators that are coming out from the bottom of the battery pack.

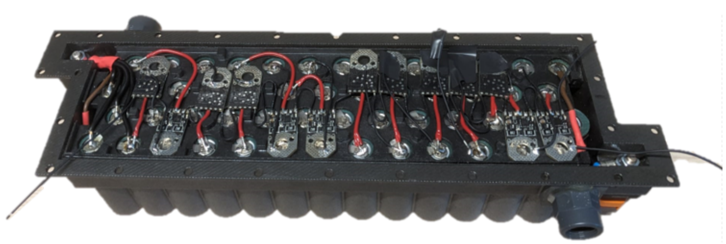


Figure 24: 13s4p battery pack seen from the bottom. Visible the busbar mount, the EMUS G1 cell modules with power and communication cables (respectively red and black), power connectors and cooling connectors. The two thin wires coming out from the casing are the extremities of an external temperature sensor

3 EMSU BMS Control Unit

3.1 Introduction to EMUS G1 Control Unit and its components

3.1.1 EMUS G1 control unit

The control of both battery packs, in terms of voltage, current, temperature and SoC can be exploited by a battery management system. In the following thesis project, such task is managed by an EMUS G1 control unit. EMUS G1 Control Unit interacts with all the first and third party components, constituting a battery pack system, this thanks by the usage of its main 22 pin and secondary 8 pin connectors. The monitoring of the entire battery state is done through the EMUS Control panel, which allows to monitor and configure more than 300 parameters.
The reason why the EMUS G1 control unit has been chosen for this project is mainly because of two reasons:

- High flexibility with lithium chemistry, since it can afford any type of Li-ion cell;
- If series connected, it can manage 80 cells contemporaneously;

The main features presented by this BMS are:

- USB data interface, for connecting with an host device when performing configuration, diagnostic and maintenance;
- RS232 data interface for checking BMS activity through third party or first party EMUS G1 BMS devices;
- Serial communication with cell boards, through top and bottom optical isolators;
- SoC and SoH algorithms, for their calculations;
- Non isolated CAN 2.0 A/B data interface, which allows communication with third and first party EMUS G1 BMS components equipped with CAN

This is the scheme of the pins:
1. Power; **2.** Ground; **3.** Cell RX+; **4.** Cell RX-; **5.** Cell TX+; **6.** Cell TX-; **7.** USB PWR; **8.** GROUND; **9.** USB D+; **10.** USB D-; **11.** DISP.TX; **12.** DISP.RX; **13.** HEATER; **14.** BAT.LOW; **15.** BUZZER; **16.** CHG.IND; **17.** CHARGER; **18.** FAST CHG; **19.** IGN.IN; **20.** AC SENSE; **21.** CAN+; **22.** CAN-; **23.** SPEED IN; **24.** SOC OUT; **25.** +5V OUT; **26.** GROUND; **27.** INPUT 4; **28.** INPUT 3; **29.** INPUT 2; **30.** INPUT 1.

The control board requires a nominal voltage that can range from 9 to 64 VDC,

Figure 25: EMUS G1 BMS

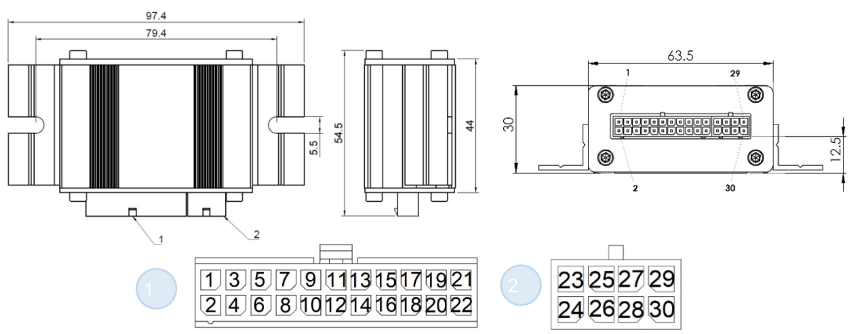


Figure 26: EMUS BMS mechanical scheme

while the minimum voltage supported is of 7 VDC and the maximum is of 72 VDC. In the following project, the EMUS G1 control board has been powered up with a 12 VDC voltage, to which corresponds a current consumption of 26 mA, which instead drops down to 13.6 mA if the voltage is doubled to 24 VDC. If to the BMS an external current sensor gets connected, to measure the current flowing through the battery pack, the current consumption goes to 39 mA for a 12 VDC supply and to 19 mA for a 24 VDC supply.

As seen from the mechanical scheme of the EMUS G1 control board, it is able to provide an output voltage of 5 V, that can be used as sensor input with an output resistance of 1 kOhm.

3.1.2 EMUS cell boards

The EMUS cell board is the device that has been chosen, in this thesis project, for measuring the cells' voltages, external temperature and internal temperatures and for communicating such values to the EMUS G1 control unit. The cell boards, using the previously mentioned parameters, are able to regulate the balancing current, so to keep each cell's voltage lower than the balancing threshold and at the same time helps keeping their own temperature below the maximum value, necessary for protecting each of them from overheating.

Such cell boards, like for the control unit, can be used with every type of Li-ion chemistry and can be connected in a daisy chain with other 79 cell boards, connected to the EMUS G1 control unit with top and bottom isolators, providing serial communication and optical isolation. Moreover, they are quite flexible because they can be used in energy storage systems, photovoltaic battery systems, onboard electric vehicles (like this case) and with the LG 21700-50G that are used in this project, which have a capacity of 4.9 Ah they guarantee also short balancing periods, since they can support cells with a capacity up to 150 Ah.

The features that are supported by the EMUS G1 cell board are the following:

- It has two integrated ports for connecting an external temperature sensor (100 kOhm NTC);
- Integrated internal temperature sensor necessary for overheating protection;
- Maximum balancing current of 1.0 A, this explains why improving the capacity of the cell to balance, the balancing time improves;
- red LED indicating balancing level;
- Communication indicating green LED;
- Digital I/O Analog, proprietary serial interface for communication;

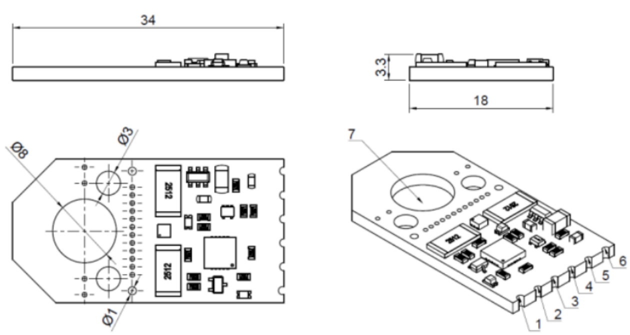


Figure 27: EMUS G1 cell board

From the mechanical scheme of the cell board, it is possible to see the presence of seven pins, these are the respective functions:
1.DN; **2.**Temperature sensor GND; **3 and 4.** CELL+; **5.**Temperature sensor

(optional); **6.** UP; **7.** CELL-.

The operating voltage and measuring range is from 2.0 VDC to 4.55 VDC, the resolution offered by the cell boards is of 10 mV and the maximum measuring error is of +- 10 mV. The maximum balancing current that can be managed at a voltage of 4.20 V is of 900 mA, while at the nominal voltage of 3.60 V is of 800 mA. The internal temperature measuring range is from -40°C to 85°C, the resolution is of 1°C and the maximum measuring error is of +-5°C. For what concerns the external temperature sensors, they offer a measuring range that goes from -99°C to 154°C, with a resolution of 1°C and a maximum measuring error of +-5°C. The communicating LED, at a supply voltage of 3.60 V, consumes a current of 2.9 mA, while when it is in sleepy mode it is of only 0.035 mA. The balancing resistor has a resistance of 4.1 Ohm and drains a power of 2 W.

3.1.3 How cell boards are connected to the control board

In the following thesis project no CAN devices are going to be connected to the entire battery system, so the connection between cell boards and EMUS control unit is quite straightforward and simple. A simple daisy chain is already enough to allow to cell boards to communicate with each others and transmits all the data to the BMS, which then will send back to the cell modules the commands to manage the battery pack. This is how the connection should be performed:

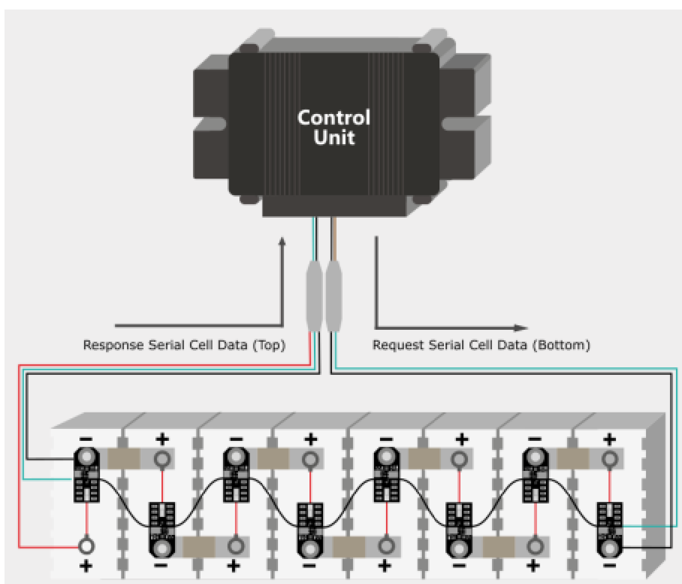


Figure 28: Daisy chain connection between cell boards and BMS

As can be seen from the picture above, considering that the battery is a 3s3p,

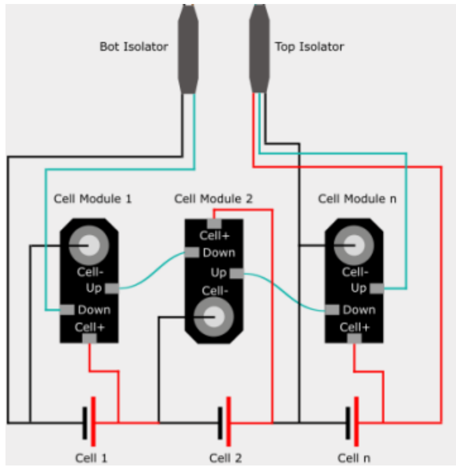


Figure 29: Scheme of connection in a 3s3p

each cell module will be connected to the extremities of a parallel made up by three cells connected in series, the CELL+ pin is going to be connected to the most positive side of the parallel, while the CELL- is going to be connected to the most negative side of the parallel. For what concerns the communication, the DN pin of the first cell board must be connected to the bottom isolator, which is the one receiving information and commands from the EMUS control board, while the UP will be connected to the DN of the second, and so on, creating a daisy chain. At the last cell board, the UP is going to be connected to the top isolator, which is the one sending info to the BMS.

From the BMS side, the isolators needs to be connected in this way:

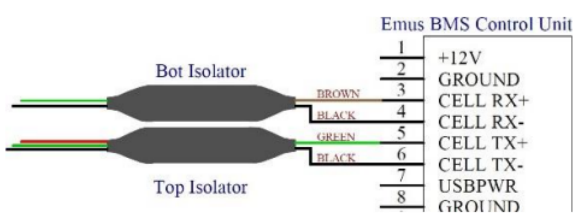


Figure 30: Top and bottom isolators, connected to the BMS

As can be seen, the top isolator, is the one that is used for allowing to cell boards the reception of the commands and data coming from the BMS, while the top isolator, since is connected to the TX pins is the one used by cell boards for transmitting the data of voltage and temperature to the BMS, data that are useful for allowing to evaluate also SoH, SoC and define the best control strategy for preserving the health of the pack, and allowing a perfect balancing of the cells, both during charging and discharging.

3.1.4 Top and bottom isolators

The EMUS top/bottom isolators are cell communication adapters providing optical isolation in all the applications where the BMS, which is the main controller, communicates directly to the EMUS cell board. The bottom isolators providing connection between the BMS and the first cell board, while the top isolator provides isolating barrier between the last cell of series-connected battery and the BMS.

Top and bottom isolators work well with every kind of lithium chemistry and they can support serial communication with up to 80 cells within a daisy chain. The serial communication protocol is going to be deeply presented in the next paragraph of the following chapter.

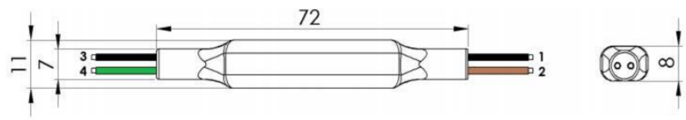


Figure 31: Bottom isolator

This is the role of each single wire:
1. Black: CELL RX-; **2.Brown**: CELL RX+; **3.Black**: TOP CELL -; **4.Green**: Up.

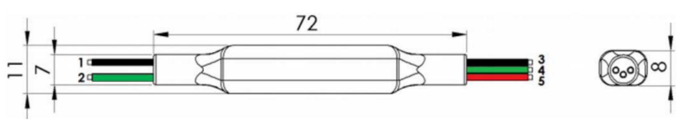


Figure 32: Top isolator

Instead, for what concerns the top isolators, these are the functions of the single wires:
1.Black: CELL TX-; **2.Brown**: CELL TX+; **3.Black**: TOP CELL-; **4.Green**: UP; **5.Red**: TOP CELL+.
Both top and bottom isolators present an isolation voltage of 2.0 kV, a transient overvoltage protection between GND and OUT of 6.2 VDC and reverse polarity protection between GND and OUT of -0.7 VDC. For what concerns the connection between TOP CELL - and UP, the overvolage protection during transient is of 5.6 VDC and the reverse polarity protection is still of -0.7 VDC. Same parameters of protection between TOP CELL- and TOP CELL+. The operating temperature range is the same of the EMUS BMS and of the cell boards, so it goes from -40°C to +85°C.

3.2 SoC and SoH evaluation algorithm

The SoC estimation in the EMUS G1 control unit can be done by using the Coulomb counting method or even the advanced Kalman filter based method, for the evaluation of SoC, SoH and SoP. the Coulomb counting is done in sync with the current update process: every newly value of current is multiplied by the small time interval of measurement and such value is accumulated inside the volatile memory as Battery Capacity in Ah. Such value is then compared with the nominal value and from this it is possible to express the SoC in percentage. The new advanced Kalman filter-based algorithm incorporates cell degradation factors and increases SoC calculations accuracy by the knowledge of the actual battery cells capacities.

3.2.1 SoC Coulomb counting method

Coulomb Counting is a standard method for the estimation of the State of Charge. It particularly depends on used current sensor characteristics and setup and it could suffer from long-term drift due to the possible presence of inaccuracies in the current measurement. So, in EMUS implementation the SOC is adjusted to 100 % every time there's the conclusion of the charging process by equating the battery charge to the value of "Capacity" configuration parameter. The following adjustment can be insufficient in some cases, like solar energy storage processes, where the charging could remain unfinished even for many days, whenever there's absence of sunlight. The optional "Reduce SOC at Under-Voltage" feature may be used. When it's enabled, the battery charge value is adjusted in such a way that the SOC would match the "SOC at Low Volt. Warn." parameter or 0 respectively whenever the Low Cell Voltage reduction or Cell Under-Voltage protection is activated. In both cases, the following conditions also need to be met for the adjustment to take place:

- The battery current must remain below 0.5 C for at least 5 seconds;
- The value of SOC that is currently estimated must be greater than that which would be after the adjustment.

Once the adjustment of a type takes place, it will only be repeated if the corresponding reduction or protection is cleared, and the SOC value becomes greater than the corresponding adjustment value before the adjustment condition is met again.

3.2.2 Integrated SoC/SoH estimator

The Coulomb Counting and Adjustment by Cell voltage are methods that can estimate only the SoC and that along with the time give a more and more degraded estimation due to the natural degradation of the cells, which factors are ignored in such algorithms. To keep the estimation of SoC always precise and also estimate the real capacity along with internal cell parameters, EMUS introduced advanced integrated SoC/SoH/SoP estimation algorithm.

Such algorithm tries to replicate the chemical behavior of lithium-ion cells, by using an equivalent electrical circuit, like this:

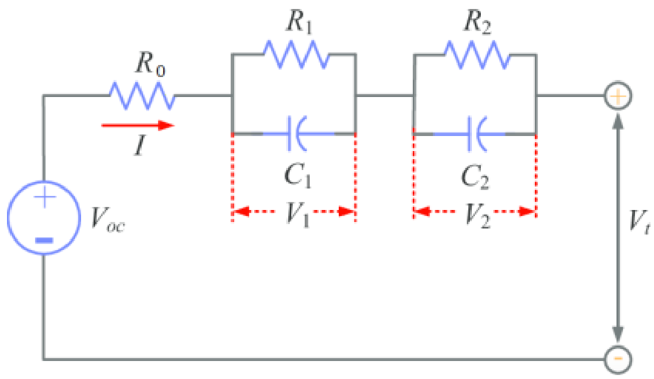


Figure 33: Li-ion cell equivalent circuit used by EMUS algorithm

The parameters characterizing the equivalent circuit are the following:

- $\mathbf{R}_0$: is the internal resistance and it is one of the variables calculated by cell model. The first value is a reference point, with the time the algorithm will adjust such value and it directly impacts the estimation of the SoC;

- $\mathbf{R}_{1,2}$: internal polarization cell resistance used for estimating and eliminating SOC counting error;

- $\mathbf{C}_{1,2}$: internal polarization cell capacitance used for estimating and eliminating SOC counting error;

- $\mathbf{V}_{OC}$: open circuit voltage;

- $\mathbf{V}_t$: terminal voltage

The accuracy of such algorithm particularity depends on the accuracy of the parameters that must be estimated during the cell installation. With advanced calculations, real cells capacity along with internal cell series resistances can be estimated. Also the quality of the current and voltage sensors that are used impacts on the quality of the estimation.

Such algorithm requires the knowledge not only of the previous listed parameters, but also the knowledge of the OCV-SOC dependency curve. While this algorithm is superior in the long run compared to other algorithms, inaccuracies during the first one or two charging discharging cycles are possible, so it's needed a certain convergence period.

3.3 EMUS BMS connected to the 13s4p battery pack

The first trial of EMUS BMS has been carried out connecting it to the only battery manufactured at the moment, the 13s4p. The process of connection is not so straightforward and it is developed into several steps, which are the following:

- **Installation of the EMUS G1 cell modules**: as seen, each cell module has two power connections, one needs to be connected to the most negative part of a parallel and the other to the most positive extremity of the parallel. For what concerns the communication cables, the DN of the first cell module needs to be connected to the bottom isolator, the UP is then connected to the DN of the next cell module and so on, creating a daisy chain, until reaching the last cell module, where the UP terminal is connected to the top isolator.

- **Connection of top and bottom isolators to the EMUS G1 Control Unit**: in the EMUS G1 Control Unit starter kit, the optical isolators are not already inserted in the connector, which instead contains the two power supply cables (red and black) and the four cables constituting the USB connection (+5 V, GND, TX and RX). So, following the instructions of the manual, such cables have been correctly connected inside the connectors, using MOLEX clips.

- **Installation of EMUS G1 Control Panel**: the setting up of the whole BMS and the monitoring of the battery status can be performed by installing in a laptop the Control Panel provided by EMUS in their website. Knowing the battery characteristic it is possible to impose all the characteristic controlling the charging, discharging process and possible warnings and protections that can be added to the battery system, so to preserve its status. The BMS needs to be connected to the laptop via USB connection, so that the control panel can recognize it, and in the meanwhile it needs to be power up with a DC voltage generator and the range of usable voltage goes from 9 V to 64 V.

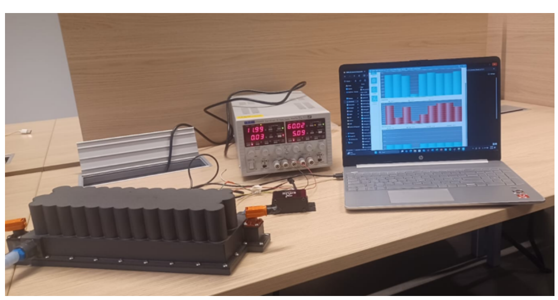


Figure 34: Battery, EMUS G1 Control Unit and laptop connected

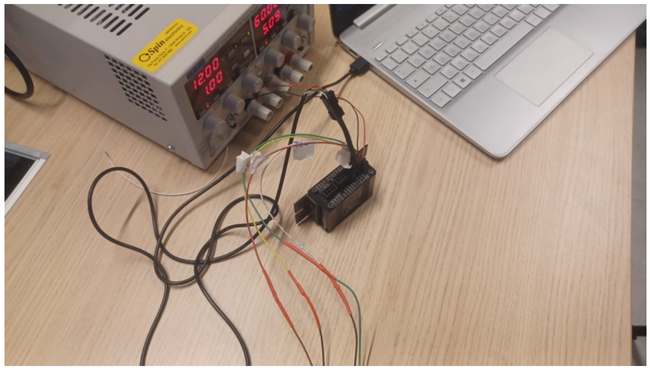


Figure 35: EMUS G1 Control Unit close up

3.3.1 What does the control panel show?

The control panel shows different menus which are the following:

- **Status**: it is the page where it is possible to monitor voltage, current temperature provided by each cell module and by the current sensor. In this page it is possible to visualize also the number of cells modules connected and communicating with each other, the status of input and output pins, the status of the sensors and of additional CAN devices. looking the picture can be seen only 12 signals instead of 13 and this because when the battery was initially tested a series connection was removed because it was damaged during the welding process and it is also possible to notice the fourth series being damaged, since it's voltage and temperatures are very low and there's no balancing current, sign that that series is not participating at the active balancing process.

Figure 36: Cell status

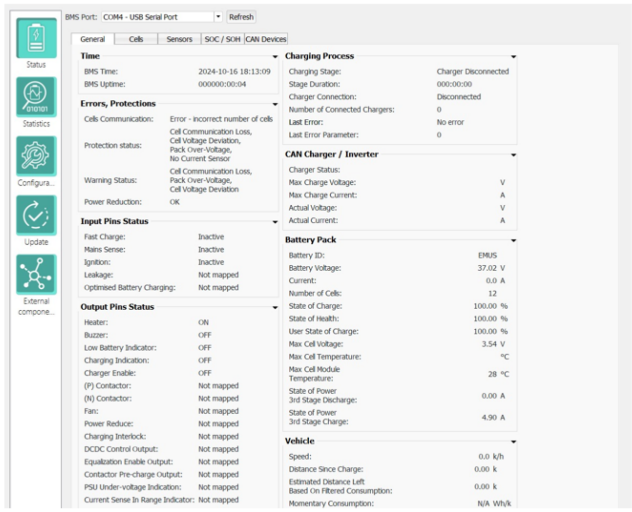


Figure 37: Status page of control panel

- **Statistics**: in this section information about maximum and minimum currents, voltage and temperatures are reported, with a message and the time of the event. In the same section there's also the event page, where all the events happening are reported.

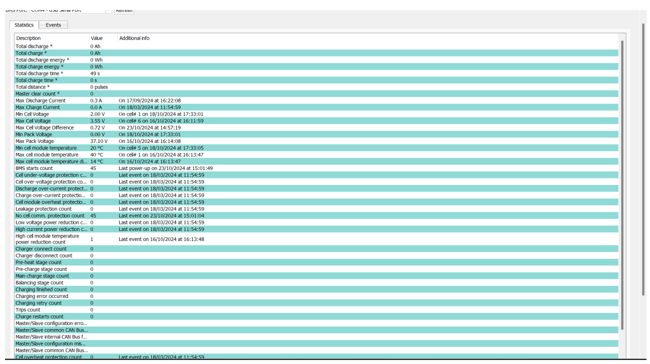
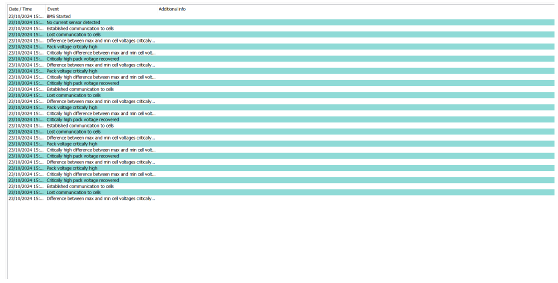


Figure 38: Statistics page

- **Configuration**: in this section, once the BMS is correctly connected to the laptop, it is possible to impose all the parameters that will control the charging, discharging processes and all the parameters that are necessary for imposing warnings and protections, that can prevent the battery facing dangerous situations like over and under voltage, over and under current, over and under temperature .

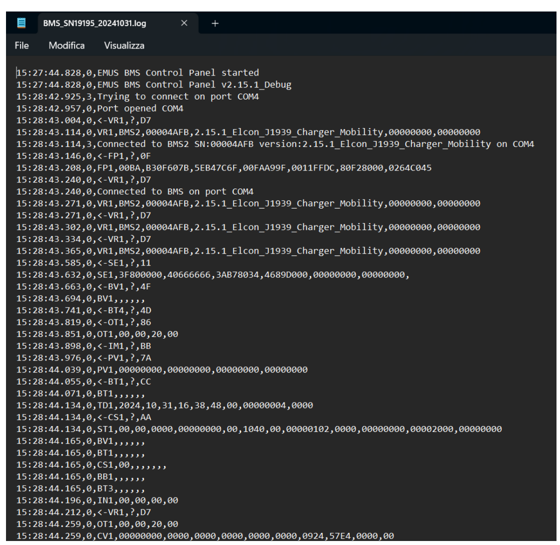


Date / Time	Event	Additional info
23/10/2024 15:...	BMS Started	
23/10/2024 15:...	No current sensor detected	
23/10/2024 15:...	Established communication to cells	
23/10/2024 15:...	Lost communication to cells	
23/10/2024 15:...	Difference between max and min cell voltages critically...	
23/10/2024 15:...	Pack voltage critically high	
23/10/2024 15:...	Critically high difference between max and min cell volt...	
23/10/2024 15:...	Critically high pack voltage recovered	
23/10/2024 15:...	Difference between max and min cell voltages critically...	
23/10/2024 15:...	Pack voltage critically high	
23/10/2024 15:...	Critically high difference between max and min cell volt...	
23/10/2024 15:...	Critically high pack voltage recovered	
23/10/2024 15:...	Established communication to cells	
23/10/2024 15:...	Lost communication to cells	
23/10/2024 15:...	Difference between max and min cell voltages critically...	
23/10/2024 15:...	Pack voltage critically high	
23/10/2024 15:...	Critically high difference between max and min cell volt...	
23/10/2024 15:...	Critically high pack voltage recovered	
23/10/2024 15:...	Established communication to cells	
23/10/2024 15:...	Lost communication to cells	
23/10/2024 15:...	Difference between max and min cell voltages critically...	
23/10/2024 15:...	Pack voltage critically high	
23/10/2024 15:...	Critically high difference between max and min cell volt...	
23/10/2024 15:...	Critically high pack voltage recovered	
23/10/2024 15:...	Difference between max and min cell voltages critically...	
23/10/2024 15:...	Pack voltage critically high	
23/10/2024 15:...	Critically high difference between max and min cell volt...	
23/10/2024 15:...	Critically high pack voltage recovered	
23/10/2024 15:...	Established communication to cells	
23/10/2024 15:...	Lost communication to cells	
23/10/2024 15:...	Difference between max and min cell voltages critically...	

Figure 39: Event page

- **Update**: in this page it is possible to update the control panel software with newer versions published by EMUS and it is possible also to update the firmware software of the BMS,
- **External components**: in this section it is possible to add external components like the closed loop current sensor or the smartphone connectivity module.

While using and monitoring the battery, the control panel is also able, by checking the voice "Event Log", to print a .txt file where are reported all the messages, written with the proprietary communication protocol. To properly understand the meaning of each message, in the next chapter the proprietary serial communication protocol is going to be presented and each message type is going to be presented.



BMS_SN19195_20241031.log

File Modifica Visualizza

```
15:27:44.828,0,EMUS BMS Control Panel started
15:27:44.828,0,EMUS BMS Control Panel v2.15.1_Debug
15:28:42.925,3,Trying to connect on port COM4
15:28:42.957,0,Port opened COM4
15:28:43.004,0,<-VR1,?,D7
15:28:43.114,0,VR1,BMS2,00004AFB,2.15.1_Elcon_J1939_Charger_Mobility,00000000,00000000
15:28:43.114,3,Connected to BMS2 SN:00004AFB version:2.15.1_Elcon_J1939_Charger_Mobility on COM4
15:28:43.146,0,<-FP1,?,0F
15:28:43.208,0,FP1,00BA,B30F607B,5EB47C6F,00FAA99F,0011FFDC,80F28000,0264C045
15:28:43.240,0,<-VR1,?,D7
15:28:43.240,0,Connected to BMS on port COM4
15:28:43.271,0,VR1,BMS2,00004AFB,2.15.1_Elcon_J1939_Charger_Mobility,00000000,00000000
15:28:43.271,0,<-VR1,?,D7
15:28:43.302,0,VR1,BMS2,00004AFB,2.15.1_Elcon_J1939_Charger_Mobility,00000000,00000000
15:28:43.334,0,<-VR1,?,D7
15:28:43.365,0,VR1,BMS2,00004AFB,2.15.1_Elcon_J1939_Charger_Mobility,00000000,00000000
15:28:43.585,0,<-SE1,?,11
15:28:43.632,0,SE1,3F800000,40666666,3AB78034,4689D000,00000000,00000000,
15:28:43.663,0,<-BV1,?,4F
15:28:43.694,0,BV1,,,,,,
15:28:43.741,0,<-BT4,?,4D
15:28:43.819,0,<-OT1,?,86
15:28:43.851,0,OT1,00,00,20,00
15:28:43.898,0,<-IM1,?,BB
15:28:43.976,0,<-PV1,?,7A
15:28:44.039,0,PV1,00000000,00000000,00000000,00000000
15:28:44.055,0,<-BT1,?,CC
15:28:44.071,0,BT1,,,,,,
15:28:44.134,0,TD1,2024,10,31,16,38,48,00,00000004,0000
15:28:44.134,0,<-CS1,?,AA
15:28:44.134,0,ST1,00,00,0000,00000000,00,1040,00,00000102,0000,00000000,00002000,00000000
15:28:44.165,0,BV1,,,,,,
15:28:44.165,0,BT1,,,,,,
15:28:44.165,0,CS1,00,,,,,,,
15:28:44.165,0,BB1,,,,,,
15:28:44.165,0,BT3,,,,,,
15:28:44.196,0,IN1,00,00,00,00
15:28:44.212,0,<-VR1,?,D7
15:28:44.259,0,OT1,00,00,20,00
15:28:44.259,0,CV1,00000000,0000,0000,0000,0000,0000,0924,57E4,0000,00
```

Figure 40: Event log .txt file

3.3.2 Firmware upgrade

Reset the Emus BMS Control Unit: Use the RS1 command or perform a reset via power-on.

- **Bootloader Mode Activation**: After reset, the control unit sends the character '#'. The upgrading device must respond with the same character within 1 second to enter bootloader mode.

- **Firmware Version Identification**: In bootloader mode, the control unit sends the VR1 command, indicating that the firmware version is 'boot'.

- **Sending Firmware Data**: The upgrading device reads the firmware update file and sends the data to the control unit in separate frames. After each frame, the control unit responds with 0x11 (successful reception) or 0x22 (CRC error).

- **Retransmission in Case of Error**: If a frame is not accepted (CRC error), the upgrading device must retransmit the rejected frame.

- **Upgrade Completion**: Once the last frame is successfully received, the control unit restarts and boots up with the newly updated firmware.

- **Firmware Update File Format**: The update file (provided by JSC "Elektromotus") is a text file where each byte is encoded with 2 symbols (from 0 to 9 and from A to F), representing the hexadecimal value of the byte. For example, '0004424D' represents the hexadecimal values 0x00, 0x04, 0x42, and 0x4D.

- **The frames in the file are organized as follows**: The first two bytes of each frame indicate the length of the following data, in big-endian order (most significant byte first). For example, in the frame '0004424D5331', the first two bytes '00' and '04' indicate that the data length is 4 bytes, followed by the data 0x42, 0x4D, 0x53, and 0x31.

- **Important Note**: The upgrading device must ignore the first 3 frames in the update file, which contain information about the hardware, firmware version, and serial number. All subsequent frames must be sent one at a time to the control unit, waiting for the 0x11 or 0x22 reply before sending the next frame.

4 Introduction to the communication protocol

EMUS BMS Control Unit is capable of communicating with external devices like laptops by using serial communication system like RS232 and USB, using a special protocol of communication. This protocol is used for sending to other devices updates about the state of a battery, or to receive messages, updates of the firmware or also for receiving information about possible changes in the configuration of the controller.

In order to establish communication with EMUS BMS Control Unit over RS232 or USB interface, the external device must use the following connection settings:

- Baud rate: 57.6 kbps;
- Data Bits: 8 bits;
- Parity: None;
- Stop Bits: 1 bit
- Hardware Flow Control: None.

4.1 General format

The general format of the messages that can be sent or can be received by the EMUDS BMS Control Unit consists in a series of frames which are divided between them by using ASCII symbols 0x0A and 0x0D, which are comma and semicolon. The first sentence is the name of the type of message, then there are the so-called Data Fields and the message ends with an 8 bit hexadecimal sentence that is the Cyclic Redundancy Check (CRC) which is calculated over all the symbols of the message and is used to check the correctness of the communication.

<CR/LF>[Sentence Name],[Data field 1],[...],[Data field n],[CRC checksum]<CR/LF>

Figure 41: Structure of a sentence

Let's give a look to an example of message:

```
ST1,00,00,0000,000128E3,07,0000,00,00040802,A2
```

Figure 42: Example of a sentence provided by or to the EMUS Control Unit

ST1 is the sentence name. The fields from the first '00' to '00040802' are the data fields. 'A2', which in hexadecimal format is 93, is the CRC. EMUS BMS can send the sentences periodically and/or upon request from an external device. Usually, the request is denoted by '?' in the data field of the sentence sent by the external device to EMUS BMS. Below, there's an example of request sentence that can be sent to EMUS BMS:

VR1 is the name of the request, D7 is the CRC and '?' is the symbol that

VR1,?,D7

Figure 43: Example of request

indicates that the message is a request. Not all the sentences support the '?' symbol. The CRC checksum is 8 bit value and it is calculated based on $X^8 + X^5 + X^4 + X^0$ polynomial with initial value 0. The function in C programming language that can be used for decoding the CRC is shown below.

```
#define CRC8INIT      0x00
#define CRC8POLY      0x18              //0X18 = X^8+X^5+X^4+X^0
uint8_t crc8 ( uint8_t *data_in, uint16_t number_of_bytes_to_read )
{
        uint8_t        crc;
        uint16_t loop_count;
        uint8_t  bit_counter;
        uint8_t  data;
        uint8_t  feedback_bit;
        crc = CRC8INIT;
        for (loop_count = 0; loop_count != number_of_bytes_to_read; loop_count++)
        {
                data = data_in[loop_count];
                bit_counter = 8;
                do {
                        feedback_bit = (crc ^ data) & 0x01;
                        if ( feedback_bit == 0x01 ) {
                                crc = crc ^ CRC8POLY;
                        }
                        crc = (crc >> 1) & 0x7F;
                        if ( feedback_bit == 0x01 ) {
                                crc = crc | 0x80;
                        }
                        data = data >> 1;
                        bit_counter--;
                } while (bit_counter > 0);
        }
        return crc;
}
```

Figure 44: C language code for calculating the CRC

4.2 Data field encoding types.

Data fields in the sentences can be encoded into different formats to represent different types of data in simple and concise ways. Formats are designed in a way in which data can be decoded or encoded with a small effort and also require a modest transmission rate.

Most of the data values are usually encoded using hexadecimal formats. The hexadecimal format uses integer numbers from ‘0’ to ‘9’ and upper capital letters from ‘A’ to ‘F’. Depending on the amount of info to transmit the number of symbols changes, in fact for transmitting an 8 bit info only 2 symbols are enough, for 16 bits 4 characters are used and for a 32 bit information 8 symbols are involved. There are several types of hexadecimal encodings:

- HexCode – This is a code of predefined meaning in hexadecimal. Usually, the predefined value meanings are the following: 0 – Normal, 1- Warning, 2 – Error, then the value ‘02’ in that field means that the EMUS BMS Controller is reporting an error;
- HexDec – This format is used whenever it is necessary to transmit signed fixed decimal numbers. Generally, there’s the code and then there’s the presence of an offset and a multiplier that are known in advance depending the kind of sentence that is transmitted or received. For example, if a code 0x8D is transmitted, it coincides with number 141, then this number needs to be summed to an offset, like -100 and the sum then gets multiplied with a multiplier like 0.1, the result is the decoded number:

$$(141_{(\text{hexadecimal 0x8D})} + (-100)) \times 0.1 = 4.1;$$

Figure 45: Conversion of hexadecimal number in floating number

- HexDecByteArray – An array of bytes that represent fixed point decimal numbers, encoded in hexadecimal. Example: if data field is specified as HexDecByteArray with offset 200 and multiplier 0.01, then the string ‘9D9F9E’ in that field encodes the following values:

$$(157_{(\text{hex 0x9D})} + 200) \times 0.01 = 3.57;$$
$$(159_{(\text{hex 0x9F})} + 200) \times 0.01 = 3.59;$$
$$(158_{(\text{hex 0x9E})} + 200) \times 0.01 = 3.58.$$

Figure 46: Conversion of a series of hexadecimal numbers in floating ones

- HexBitBool – A set of Boolean values, where each bit of a byte represents a separate logical value, encoded in hexadecimal. For example, if data field description specifies that bit 0 represents “Under-voltage” flag, and bit 1 represents “Over-Voltage” flag, then value ’02’ in that data field means that “Over-voltage” flag is active.

Then there's also the decimal encoding, in which a signed or unsigned integers are represented in their usual decimal format.

4.3 Sentences

The content of the sentences can change with newer versions of the EMUS BMS Control Unit firmware. For application backwards-compatibility, it is advisable to leave more fields in the sentence when EMUS BMS is integrated with an external device. It is important to check the CRC of the full sentence, regardless of the number of fields in it. Individual data field can also change with newer versions, so it is advisable to rely on comma delimiters.

BB1 – Battery Balancing Rate Summary Sentence

This sentence is used for showing a summary of the cell balancing rates of the battery pack. It is sent periodically, in configurable time intervals for both active and sleep states. If a request of sent, the '?' is present in the middle of the sentence. When an error in the communication occurs, all the fields, except the name one and the CRC are empty. The Balancing Current is evaluated as the ratio between the cell voltage and the shunt resistance of that cell, multiplied by the balancing current rate:

Balancing current [A] = (cell voltage [V] / shunt resistance [Ohm]) x (balancing rate / 100)

Field #	Value meaning	Format	Description
1	NUMBER OF CELLS	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Number of cells that are detected through communication channel.
2	MIN CELL BALANCING RATE	HexDec unsigned offset: 0 multiplier: 100/255 result: unsigned unit: %	Lowest cell module balancing rate in the battery pack.
3	MAX CELL BALANCING RATE	HexDec unsigned offset: 0 multiplier: 100/255 result: unsigned unit: %	Highest cell module balancing rate in the battery pack.
4	AVERAGE CELL BALANCING RATE	HexDec unsigned offset: 0 multiplier: 100/255 result: unsigned unit: %	Average cell module balancing rate in the battery pack.
5	Empty field		An empty field for backward compatibility.
6	BALANCING VOLTAGE THRESHOLD	HexDec unsigned offset: 200 multiplier: 0.01 result: unsigned unit: V	Balancing voltage threshold: if cell voltage is above this threshold, cell module starts balancing.

Figure 47: Structure of BB1 sentence

BB2 - Battery balancing detail sentence

The following sentence is used for having a summary of the balancing state of cells within a group. The number of cells inside a group can go from 1 to 8. The following sentence is sent only after EMUS BMS Control Unit receives a request sentence from external device, where the only data field is '?' symbol.

```
BB2,00,0000,08,0000000000000000,45
BB2,00,0008,08,0000000000000000,99
BB2,00,0010,08,0000000000000000,D7
BB2,00,0018,08,0000000000000000,0B
BB2,00,0020,08,0000000000000000,78
BB2,01,0028,08,0000000000000000,42
BB2,01,0030,08,0000000000000000,0C
BB2,01,0038,08,0000000000000000,D0
BB2,01,0040,08,0000000000000000,D9
BB2,01,0048,08,0000000000000000,05
```

Figure 48: Example of BB2 sentences

If EMUS BMS Control Unit cannot communicate to cell modules, the data fields are empty, like in this case:

```
BB2,,,,,,,E4
```

Figure 49: Error in the communication of BB2 sentence

Field #	Value meaning	Format	Description
1	CELL STRING NUMBER	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Cell string number, to which the group of cells belong. This help identify the actual position of the group if the battery pack consists of several parallel cell strings. If only one string is used, this field is 0.
2	CELL NUMBER OF FIRST CELL IN GROUP	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Cell number of the first cell in the group. Cells are numbered from 0, and the numbering does not reset if several parallel strings are used: if battery pack consists of two parallel strings with 40 cells in each string, then the last cell in the first string is number 39, and the first cell in the second string is number 40.
3	SIZE OF GROUP	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Size of the group of cells.
4	INDIVIDUAL CELL MODULE BALANCING RATE	HexDecByteArray unsigned offset: 0 multiplier: 100/255 result: unsigned unit: %	An array containing cell module balancing rates of cells in the group.

Figure 50: Structure of BB2 sentence

BC1- Battery Charge Sentence

The following sentence contains info about the SoC of the entire battery pack. It can be sent periodically, or under request, with a sentence that contains the '?' symbol inside. Example:

Field #	Value meaning	Format	Description
1	BATTERY CHARGE	HexDec unsigned offset: 0 multiplier: 1 result: unsigned unit: C	The estimated charge of battery pack in Coulombs. One Ah is equal to 3600 Coulombs.
2	BATTERY CAPACITY	HexDec unsigned offset: 0 multiplier: 1 result: unsigned unit: C	Capacity of battery pack in Coulombs. One Ah is equal to 3600 Coulombs.
3	STATE OF CHARGE	HexDec signed offset: 0 multiplier: 0.01 result: signed unit: %	Estimated state of charge.

Figure 51: Structure of BC1 sentence

BT1 - Battery Cell Module Temperature Summary Sentence

The following sentence is used for having a summary about the cell modules temperature values of the battery pack. This sentence is sent periodically, with configurable time intervals for active and sleep states. Example:

```
BT1,0050,78,7A,78,,1A
```

Figure 52: Example of BT1 sentence

As for the previous sentences, it can be requested by request sentence from external device, where only the '?' symbol field is filled. If the EMUS BMS Control Unit cannot communicate to cell modules, the data fields are empty, let's see an example:

```
BT1,,,,,,F9
```

Figure 53: Error in BT1 sentence

Field #	Value meaning	Format	Description
1	NUMBER OF CELLS	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Number of cells that are detected through communication channel.
2	MIN CELL MODULE TEMPERATURE	HexDec unsigned offset: -100 multiplier: 1 result: signed unit: °C	Lowest cell module temperature in the battery pack.
3	MAX CELL MODULE TEMPERATURE	HexDec unsigned offset: -100 multiplier: 1 result: signed unit: °C	Highest cell module temperature in the battery pack.
4	AVERAGE CELL MODULE TEMPERATURE	HexDec unsigned offset: -100 multiplier: 1 result: signed unit: °C	Average cell module temperature in the battery pack.
5	Empty field		An empty field for backward compatibility.

Figure 54: Structure of BT1 sentence

BT2 - Battery Cell Module Temperature Detail Sentence

This sentence is used for having a summary about the temperature state of cells within groups. As for the BB2 sentence, the cells within a group can vary from 1 to 8 and this sentence can be sent only under request sentence sent from an external device, where the only data field is '?' symbol. The normal response to BT2 request message, when battery pack is made up of two parallel cell strings is like this:

```
BT2,00,0000,08,7778787878787878,0C
BT2,00,0008,08,7878787878787878,5B
BT2,00,0010,08,7877787778787878,D6
BT2,00,0018,08,7878787778787777,35
BT2,00,0020,08,7878777877787877,32
BT2,01,0028,08,7778777878777777,C7
BT2,01,0030,08,7777787878787778,62
BT2,01,0038,08,7878787877787878,E8
BT2,01,0040,08,7778777878787878,FA
BT2,01,0048,08,7878787777787878,43
```

Figure 55: Example of BT2 sentences

If EMUS BMS Control Unit cannot communicate to cell modules, the data fields are empty, like this:

```
BT2,,,,,,,AD
```

Figure 56: Error in BT2 sentence

Field #	Value meaning	Format	Description
1	CELL STRING NUMBER	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Cell string number, to which the group of cells belong. This help identify the actual position of the group if the battery pack consists of several parallel cell strings. If only one string is used, this field is 0.
2	CELL NUMBER OF FIRST CELL IN GROUP	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Cell number of the first cell in the group. Cells are numbered from 0, and the numbering does not reset if several parallel strings are used: if battery pack consists of two parallel strings with 40 cells in each string, then the last cell in the first string is number 39, and the first cell in the second string is number 40.
3	SIZE OF GROUP	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Size of the group of cells.
4	INDIVIDUAL CELL MODULE TEMPERATURES	HexDecByteArray unsigned offset: -100 multiplier: 1 result: signed unit: °C	An array containing cell module temperatures of cells in the group.

Figure 57: Structure of BT2 sentence

BT3 - Battery Cell Temperature Summary Sentence

It is exactly like the BT1, same meaning of each field, same format, the only difference is the name of the sentence.

BT4 – Battery Cell Temperature Detail Sentence

It is exactly like the BT2, same meaning of each field, same format, the only difference is the name of the sentence.

Battery Voltage Summary Sentence

This sentence contains a summary of cell voltages of the battery pack. It is sent periodically, with configurable time intervals, or it can also be sent under request, by using a request sentence, which contains the '?' symbol:

```
BV1,0050,4A,94,80,335B,,D3
```

Figure 58: Example of BV1 sentence

If EMUS BMS Control Unit cannot communicate to cell modules, the data fields are empty, like in the following example:

```
BV1,,,,,,,39
```

Figure 59: Error in the BV1 sentence

Field #	Value meaning	Format	Description
1	NUMBER OF CELLS	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Number of cells that are detected through communication channel.
2	MIN CELL VOLTAGE	HexDec unsigned offset: 200 multiplier: 0.01 result: unsigned unit: V	Lowest cell voltage in the battery pack.
3	MAX CELL VOLTAGE	HexDec unsigned unsigned offset: 200 multiplier: 0.01 result: unsigned unit: V	Highest cell voltage in the battery pack.
4	AVERAGE CELL VOLTAGE	HexDec unsigned offset: 200 multiplier: 0.01 result: unsigned unit: V	Average cell voltage in the battery pack.
5	TOTAL VOLTAGE	HexDec unsigned offset: 0 multiplier: 0.01 result: unsigned unit: V	Total voltage of all cells in the battery pack.
6	Empty field		An empty field for backward compatibility.

Figure 60: Structure of BV1 sentence

BV2 - Battery Voltage Detail Sentence

This sentence contains a recap of the voltage state of cells within a group. It can be sent only under request of an external device, by using a request sentence, where the only data field is '?' symbol.

```
BV2,00,0000,08,8B85858585868587,93
BV2,00,0008,08,878782807D7F7F7D,A8
BV2,00,0010,08,7F83848365717E6D,00
BV2,00,0018,08,8585838482828075,8E
BV2,00,0020,08,7B7E817F7B718B8A,53
BV2,01,0028,08,828C8B9392899188,71
BV2,01,0030,08,829394928E8E8E96,7B
BV2,01,0038,08,898C8A928A8A897E,40
BV2,01,0040,08,83848B8B818C818C,C6
BV2,01,0048,08,878686888F787A8E,9D
```

Figure 61: BV2 -sentences example

If EMUS BMS Control Unit cannot communicate to cell modules, the data fields are empty

```
BV2,,,,,,,FC
```

Figure 62: Error in BV2 sentence

Field #	Value meaning	Format	Description
1	CELL STRING NUMBER	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Cell string number, to which the group of cells belong. This help identify the actual position of the group if the battery pack consists of several parallel cell strings. If only one string is used, this field is 0.
2	CELL NUMBER OF FIRST CELL IN GROUP	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Cell number of the first cell in the group. Cells are numbered from 0, and the numbering does not reset if several parallel strings are used: if battery pack consists of two parallel strings with 40 cells in each string, then the last cell in the first string is number 39, and the first cell in the second string is number 40.
3	SIZE OF GROUP	HexDec unsigned offset: 0 multiplier: 1 result: unsigned	Size of the group of cells.
4	INDIVIDUAL CELL VOLTAGES	HexDecByteArray unsigned offset: 200 multiplier: 0.01 result: unsigned unit: V	An array containing voltages of cells in the group

Figure 63: Structure of BV2 sentence

CF2 - Parameter Configuration Sentence

This sentence it is used whenever it is necessary to change values of the EMUS BMS Configuration parameters. To retrieve the value of a certain parameter, a request sentence with the ID code must be sent to the EMUS Control Unit. The EMUS will respond with the same sentence, but instead of the '?' symbol, there will be the value of that specific parameter.

```
CF2,0C0E,00,C0
```

Figure 64: EMUS BMS CF2 reply

Field #	Value meaning	Format	Description
1	PARAMETER ID	HexDec unsigned Offset: 0 Multiplier: 1 Result: unsigned	The ID of parameter. List of parameter IDs and description of corresponding parameters are given in the “Parameter meaning by ID” table at the end of this document.
2	PARAMETER DATA	HexDec	Parameter value. Multiplier, offset and sign depends on the parameter, and are specified for each parameter separately in “Parameter meaning by ID” table at the end of this document.

Figure 65: CF2 sentence structure

CS1 - Charger Status Sentence

This sentence is used for communicating the parameters related to the status of the charger . It is sent periodically, with configurable intervals for both active and sleep mode. Like, for the other sentences, it can be sent also by using a request sentence, using the symbol ’?’.

```
CS1,01,00,0B90,0062,0B90,0060,64
```

Figure 66: CS1 - Charger Status Sentence

Field #	Value meaning	Format	Description
1	NUMBER OF CONNECTED CHARGERS	HexCode	Number of parallel connected chargers currently communicating with the Control Unit.
2	CAN CHARGER STATUS	HexCode	CAN charger’s status byte. For values meaning please consult charger’s manual. For non-CAN chargers, this field is empty.
3	SET VOLTAGE	HexDec unsigned offset: 0 multiplier: 0.1 result: unsigned unit: V	Charging voltage that is determined by Emus BMS Control Unit, and sent to the CAN-based charger. For non-CAN chargers this field is empty.
4	SET CURRENT	HexDec unsigned offset: 0 multiplier: 0.1 result: unsigned unit: A	Charging current that is determined by Emus BMS Control Unit, and sent to the CAN-based charger. For non-CAN chargers this field is empty.
5	ACTUAL VOLTAGE	HexDec unsigned offset: 0 multiplier: 0.1 result: unsigned unit: V	Actual charging voltage reported by the charger to Emus BMS Control Unit. If charger type does not provide actual charging voltage information, or non-CAN charger is used, this field is empty.
6	ACTUAL CURRENT	HexDec unsigned offset: 0 multiplier: 0.1 result: unsigned unit: A	Actual charging current reported by the charger to Emus BMS Control Unit. If charger type does not provide actual charging current information, or non-CAN charger is used, this field is empty.

Figure 67: CS1- sentence structure

CV1 - "Current and Voltage" Sentence

This sentence contains the values of battery voltage and current, measured by the EMUS BMS. It is sent periodically with configurable time intervals for active and sleep states (Data Transmission to Display Periods).

Field #	Value meaning	Format	Description
1	TOTAL VOLTAGE	HexDec unsigned offset: 0 multiplier: 0.01 result: unsigned unit: V	Total voltage of the battery pack.
2	CURRENT	HexDec signed offset: 0 multiplier: 0.1 result: signed unit: A	Current which is flowing through the battery pack. Positive value indicates charge current, negative value – discharge current.
3 – 10	Reserved internal		Internal BMS operation parameters that are used for BMS current measurement diagnostics from generated customer log files. Subject to change in next firmware releases.

Figure 68: CV1- sentence structure

```
CV1,000015AD,0004,01FF,01FD,01FA,03FC,09DA,66CF,0000,0000,DE
```

Figure 69: CV1 -"Current and Voltage" sentence example

DT1 - Distance and Energy Status Sentence

This sentence contains information about the distance and energy which are or measured or estimated by the EMUS BMS Control Unit. It is sent periodically with configurable time intervals for active and sleep states (Data Transmission to Display Period).

As for the other sentences, it can be sent under request, by sending a DT1 request sentence, from an external device, to the EMUS BMS Control Unit.

```
DT1,0078,000000DD,00000057,000045B4,00000003,00000001,79
```

Figure 70: DT1 - sentence example

FD1 - "Factory Defaults" Sentence

This sentence is used to reset the EMUS BMS to its factory configuration in terms of statistics and also event log, leaving the parameters field empty.

FD1,,E2

Figure 71: FD1 - "Factory Defaults" Sentence

IN1 - Input Pins Status Sentence

The following sentence is sent whenever it is necessary to know the state of the input pins of the EMUS BMS. It can be sent periodically, or under request of external devices by using the sentence request, which contains the symbol '?' inside.

IN1,50,00,00,00,B9

Figure 72: IN1 sentence

Field #	Value meaning	Format	Description
1	Reserved	HexBitBool Bit: 0-3	Bits 0 to 3 are reserved.
	AC SENSE	HexBitBool Bit: 4	AC SENSE input pin digital status.
	IGN. IN.	HexBitBool Bit: 5	IGN IN input pin digital status.
	FAST CHG.	HexBitBool Bit: 6	FAST CHG input pin digital status.
2-4	Reserved		

Figure 73: IN1 - sentence structure

LG1 - Events Log Sentence

This sentence is sent whenever it is necessary to retrieve the events log of the EMUS BMS. It is sent under request sentence, containing the symbol '?', by using an external device. The vent log can be erased by using the symbol 'c' as sentence parameter.

```
LG1,?,ED
LG1,c,D7
```

Figure 74: LG1 - Events Log Sentence example

Field #	Value meaning	Format	Description
1	LOG EVENT SEQUENCE NUMBER	HexDec unsigned Offset: 0 Multiplier: 1 Result: unsigned	Sequence number of log event where lowest number shows most recent event.
2	LOG EVENT IDENTIFIER	HexCode	Identifier of log event. Meanings: 0 – No event; 1 – BMS Started; 2 – Lost communication to cells; 3 – Established communication to cells; 4 – Cells voltage critically low; 5 – Critical low voltage recovered; 6 – Cells voltage critically high; 7 – Critical high voltage recovered; 8 – Discharge current critically high; 9 – Discharge critical high current recovered; 10 – Charge current critically high; 11 – Charge critical high current recovered; 12 – Cell module temperature critically high; 13 – Critical high cell module temperature recovered; 14 – Leakage detected; 15 – Leakage recovered; 16 – Warning: Low voltage - reducing power; 17 – Power reduction due to low voltage recovered; 18 – Warning: High current - reducing power; 19 – Power reduction due to high current recovered; 20 – Warning: High cell module temperature - reducing power; 21 – Power reduction due to high cell module temperature recovered; 22 – Charger connected; 23 – Charger disconnected; 24 – Started pre-heating stage; 25 – Started pre-charging stage; 26 – Started main charging stage; 27 – Started balancing stage; 28 – Charging finished; 29 – Charging error occurred; 30 – Retrying charging; 31 – Restarting charging; 42 – Cell temperature critically high; 43 – Critically high cell temperature recovered; 44 – Warning: High cell temperature – reducing power; 45 – Power reduction due to high cell temperature recovered.
3	EVENT PARAMETER	Reserved	Reserved
4	TIMESTAMP	HexDec unsigned Offset: 0 Multiplier: 1 Result: unsigned	The timestamp of event occurrence coded in number of seconds since January 1, 2000 time 00:00.

Figure 75: LG1 - sentence structure

OT1 - Output Pins Status Sentence

The following sentence is sent periodically with configurable time intervals for active and sleep states and contains the info about the states of the EMUS BMS control unit outputs. As usual, it can be also sent under request by sending a request sentence, where the only data field is '?' symbol.

```
OT1,80,00,80,00,14
```

Figure 76: OT1- sentence example

Field #	Value meaning	Format	Description
1	CHARGER	HexBitBool Bit: 7	CHARGER output pin digital status
2	Reserved		
3	HEATER	HexBitBool Bit: 4	HEATER output pin digital status
	BAT. LOW	HexBitBool Bit: 5	BAT. LOW output pin digital status
	BUZZER	HexBitBool Bit: 6	BUZZER output pin digital status
	CHG. IND.	HexBitBool Bit: 7	CHG. IND. output pin digital status
4	Reserved		

Figure 77: OT1 - sentence structure

PW1 - Password Submission and Authentication Query Sentence

The following sentence is necessary to login and log out or to request an authentication status, depending on the sentence parameter. Sending '?' symbol as a sentence parameter requests authentication status from EMUS Control Unit. To log into level 1 is necessary a previous access in level 0, while for accessing in level 2 is necessary to access previously in level 1. Sending '?' symbol as a sentence parameter requests authentication status from EMUS BMS Control Unit. Let's see the following examples:

```
PW1,?,B7
PW1,mypass12,27
PW1,,B2
```

Figure 78: PW1 - sentence example

Field #	Value meaning	Format	Description
1	AUTHENTICATION STATUS	HexCode	Authentication status: Meanings: 0 – Logged out, access level 0; 1 – Logged in, access level 1; 2 – Logged in, access level 2; ? – Log in request. Emus BMS Control Unit may send this request if user atempts to execute an action that requires logging in.

Figure 79: PW1 - Sentence Structure

PW2 - "Set New Password" Sentence

This sentence is used to set or clear Emus BMS Control passwords. The sentence parameter field should consist of 4 to 8 characters long string. Level 1 password is set if current access level is 1, and level 2 password is set if current access level is 2. Clearing a password can be done by sending an empty string while logged into corresponding access level. Examples in respective order.

```
PW2,mypass12,41
PW2,,56
```

Figure 80: PW2 - sentence example

Field #	Value meaning	Format	Description
1	PASSWORD SET RESULT	HexCode	Result of the attempt to set a new password. Meanings: 0 – Setting password failed; 1 – Setting password succeeded

Figure 81: Enter Caption

RC1 - "Reset Current to Zero" Sentence

it is a sentence that is used for resetting the sensor's reading to 0 A, after the current sensor is initially installed in the user's application.

```
RS1,,3F
```

Figure 82: Reset Control Unit sentence

RS2 - Reset Source History Log Sentence

It is used for retrieving the reset source history log. It is requested by the EMUS Control panel when the BMS is connected to the laptop and it gets written in the log file.

```
RS2,1BCAB37C,40,1BCAB16F,04,1BCAB16D,05,1BCAB168,04,1BCAB167,05,DF
```

Figure 83: Reset Source History Log Sentence

SC1 - "Set State of Charge" Sentence

It is a sentence imposed by an external device and it is sent for setting the current state of charge of the battery in %.

`SC1,64,E5` (sets 100% SoC)

Figure 84: SC1 - "set State of Charge" sentence

SS1 - Statistics Sentence

This sentence is used for retrieving the statistics of the EMUS Control Unit. The request sentence can be easily recognized since it contains the '?' symbol.

Any statistics has its own identifier that can be found within the EMUS Serial Protocol Manual.

```
SS1,?,F1
SS1,01,90
SS1,c,CB
```

Figure 85: SS1 - Statistics Sentence

ST1 - BMS status sentence

This sentence is used for indicating the overall status of the BMS operation and it is sent periodically with configurable time intervals, in both active and sleep states. It can be also requested by request sentence, from external devices, by adding the symbol '?'.

```
ST1,00,00,0000,000128E3,07,0000,00,00040802,93
```

Figure 86: ST1 - BMS Status Sentence

TD1 - Time and date Sentence

This sentence contains the date and the time value of EMUS BMS Control unit's internal clock. It is sent periodically with configurable time intervals, for active and sleep states.

```
TD1,2014,10,07,14,50,07,00,000003E5,60
```

Figure 87: Time and date Sentence

TC1 - "Cell Module internal temperature sensor calibration"

This sentence is intended to set the reference temperature of the cell modules and should be sent by an external device. The reference temperature value corresponds to the ambient temperature of the room where the battery is stored, and it must be measured using an external thermometer. The measured value should be applied as the parameter in this sentence, using the HexDec unsigned format, with an offset of -100 and a multiplier of 1. Cell module temperature calibration should only be performed once, after assembling the cell modules onto the cells.

`TC1,78,B0` (sets +20°C reference temperature to all cell modules)

Figure 88: TC1 - "Cell module internal temperature sensor calibration" sentence

5 Bluetooth technology

5.1 Introduction to Bluetooth communication

Bluetooth 5.0 is the fifth generation of the wireless communication technology called Bluetooth. Such technology was developed by the cooperation of companies like Ericsson, Sony, IBM, Intel, Toshiba, Nokia and other societies and its formal constitution is dated back to the 20th may 1999.

Typically, devices equipped with Bluetooth system mount a chip that allows to communicate and send data over short distance areas (historically from 10 m to 30 m), developing in this way an area called Personal Area Network (PAN).

Back in the days the Bluetooth technology has been developed with the idea to allow the communication between electronic devices with a small energy consumption, so to not impact over the life of their batteries. The ray of action can vary from 100 m for Class 1 devices to 1 m for Class 3 devices. To give an idea about the widespread of such technology, on the 4th January 2007 the n umber of devices using such technology has overcome the billion of units. Bluetooth uses the ISM band at 2.4 GHz, which is divided in 79 channels. The protocol defines the way in which the band is divided in such channels and the frequency hopping is of 1600 Hz, which means 1600 changes of channels per second.

With versions 1.1 and 1.2 the data rate was fixed at 723,1 kbits/s. From version 2.0 the data rate has been improved to 3 Mbit/s but such improvement in the speed of transfer of the data has been paid with an increment of electric energy consumed and so with a major impact over the batteries of the devices. With version 4.0 the data rate has been improved to 4 Mbit/s but thanks to the decrement of the time duration of the signals, at parity of data transferred, the energy consumption has been halved, if compared with version 1.2.

Bluetooth is not a standard comparable with the WiFi, this because this last one is a protocol that has been developed for transferring data with a much higher data rate and for covering a much larger area. In fact, with a Bluetooth system it's possible to develop only a PAN, while with WiFi it's possible to develop a Local Area Network (LAN) and it requires a much more complex hardware.

The very first car manufacturer that has introduced Bluetooth system onboard vehicles has been BMW, developing the system that allows to respond to phone calls without constraining the driver to keep its hands off from the steering wheel. Today research about the usage of Bluetooth system onboard vehicles is more concentrated on the development of wireless technologies for monitoring the state of charge and of life of battery packs onboard BEVs, so to achieve a reduction of the entire vehicle.

5.2 Class of devices

Bluetooth devices are divided into 4 classes, depending two voices which are:

- ERP Power: it's the maximum transmissive power in radiofrequency, and it comprises the increment due to the device's antenna gain;

- Distance: it's the maximum ray of coverage without considering the presence of obstacles.

Class	ERP Power (mW)	ERP Power (dBm)	Distance (m)
1	100	20	~100
2	2,5	4	~10
3	1	0	~1
4	0,5	-3	~0,5

Figure 89: Class of devices

5.3 Clock and temporization

Like in every communication network, also in a Bluetooth network the synchronization between the devices is necessary. Th real time clock signal is used for synchronizing the exchange of data between the devices, distinguishing the packets re-transmitted or lost and also for producing a predictable pseudo-random sequence of channels that are going to be occupied during the communication. Every device equipped with Bluetooth system has a 28-bit digital electronic oscillating circuit that defines that clock signal with a period of 312,5 μs (half slot). This circuit can develop clock signals for an entire day (312,5 μs x 228 23,3 h) and it starts from 0 when the device is turned on.

Every Bluetooth device has its own native clock signal (CLKN) that controls the temporization of the device. But this is not the only clock signal, in fact there are other two:

- CLK which is the CLKN of the master that then becomes the clock signal of every slave inside the piconet (a piconet is the network made by master and slaves). This happens by adding an offset to the CLKN of every slave, so that it will coincide with the CLK of the piconet;

- CLKE derives from the CLKN of the master, again adding another offset and it is used by this one during the process of connection of a new slave inside the piconet.

Generally, the first two bits of the clock signal are used for defining who is sending or transmitting, and also for defining if it's a transmission or a reception. For example CLK [1:0]= 00 means that master will start a transmission, while CLK[1:0] = 10 means that slave will start a transmission.

5.4 Connections

Every device which is connected to a Bluetooth network is recognizable by using a 24 bit code COD, such code allows also to activate the right services. There are two different types of connections that can be established:

- Without connection (connectionless), also called Asynchornous ConnectionLess (ACL): it does not require any connection before sending the packets of data, the transmitter can start in any moment the transmission of data, obviously the needed condition is that the transmitter knows the address of the device to which is sending the packets;

- Connection Oriented also called Synchronous Connection Oriented SCO where a previous connection between devices is required before sending the data;

The ACL is based on a best effort type of service and it allows to support point-multipoint connections and connection with packets commutation. Moreover, there are two different types of connections that are supported: symmetric and asymmetric. In the symmetric one a data rate of 433,9 kbit/s in both directions of transmission is supported, while in the asymmetric one a data rate of 723,2 kbit/s is allowed in a direction and of 57,6 kbit/s in the opposite direction. This kind of communication is used just for transmitting control packets and user type packets. The slave can send only if in the previous slot it received a packet from the master and in case a packet is lost the re-transmission is allowed

SCO is a connection which supports real-time data traffic. This kind of communication allows connection point to point, symmetric connections and connection with commutation of circuit. This kind of communication is used for the transmission of voice in 64 kbit/s channels. A master can manage three contemporaneous SCO connections to the same slave o with different salves which belong to the same piconet. A slave, instead, can support three SCO connections with the same master, or with two different masters. Since it is a real-time transmission, lags in the transmission of the packets is normal, but in case a packet is lost no re-transmission is allowed.

5.5 Type of networks

Two or more devices connected create a piconet. In a piconet there are two main actors:

- Master: is the device which defines the hopping sequence and its CLKN (native clock signal) becomes the clock of the entire piconet. A master can be also connected to another piconet, but in this case it will behave as a slave;

- Slave: it is the unit which is synchronized with the clock of the master and it follows the hopping frequency decided by the master. A slave can belong to more piconet at the same time and this is possible by using a Time Division Multiplexing algorithm, and it can act as a master, but just in one of them.

Bluetooth specs can define three different kinds of networks:

- Point to point, where the communication happens between a master and a slave;
- Point to multipoints: the communication happens between a master and several slaves;
- Scatternet: where two or more piconets are connected between each other, creating a bigger network;

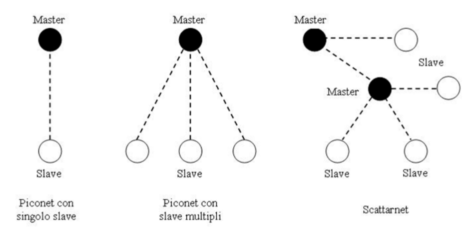


Figure 90: Possible types of connections in Bluetooth environment

Obviously, improving the number of master and slaves within a piconet can create an important problem: more collisions of data packages and so more delay in the communication and a downgrade of the performances of the network. Every piconet is independent from the others in terms of clock signal and hopping sequence, since every piconet has its own master.

In case of Class 1 devices, that allow a ray of communication of 100 m there's the possibility of creating a wireless LAN network with a maximum of seven slave devices. The great limitation of such network is that only a single slave can communicate with the master at a time. A slave can also connect to other LAN network but in this case it is recommended to put a security PIN for allowing access only to authorized devices.

A Bluetooth device can be found typically into two different states which are:

- Connection State: where the device is connected to others and it is involved in the normal operations of a piconet;
- Standby state: where the device is not connected to others, or it is not involved into normal operations of the piconet. This state has been conceived for allowing to save energy, because if a device is not involved to the normal operations of the piconet has not reason to absorb the energy peaks of the network.

Anyway, whenever a device passes from the standby state to the connection state it can be allocated in four of these modes:

- Active State: the device actively participates at the activities of the piconet, both in transmission and reception and it gets synchronized with the clock signal of the master. The master regularly transmits so to maintain the synchronization of the network. To slaves a 3 bit code, called AM_{ADDR} (Active Member Code) is given;

- Hold mode: master can put slave devices into this mode for a determinate amount of time. During this period master cannot send any packet to slaves, but it transmits just to maintain the synchronization of them. This mode gets used only when no packets have to be sent for a long interval of time. The hold mode is typically used whenever a device wants to discover other Bluetooth equipped devices or wants to make discover itself, so to join a piconet;

- Sniff mode: in sniff mode a sniff interval and a sniff offset gets determined by the master. Master can only sent packets within the sniff intervals which are determined by the sniff offset. In the meanwhile, slave hears in more reduced intervals. The passage in sniff mode can be asked by both slave and master;

- Park mode: in park mode the master gives to the slave an 8-bit code instead of the 3-bit AM_{ADDR} code. This code is called PM_{ADDR} Park Mode Address and it allows to more than seven slave to join a piconet. Salves in park mode can hear the broadcast messages and can remain synchronized with the clock signal of the master, but they do not participate to any activity of the piconet. Until 255*(28-1) devices can be allocated in Park Mode. A slave can pass in Active state only if it receives the Active Request (AR_{ADDR}) by the master.

5.6 Architecture

Like for WiFi, even for Bluetooth there's a Protocol Stack which gets divided into two macro levels that are at:

- Physical level where communication signals and connections are managed;

- Baseband: it defines the connections between devices inside the piconet. This level is based on processes of inquiry and paging to allow the synchronization of Bluetooth devices. It allows to define two different types of connections, which are ACL and SCO;

- LMP: it is responsible for the organization of the connection, control of Bluetooth devices and control of them and also for the negotiation of some packets. It is used also for making control on different modalities of power management (park, sniff and hold) and on the connection state of a device within a piconet. These last messages are filtered and managed at link manager level, so they are not transmitted at higher levels and they have an higher priority respect the user data packages.

- RFCOMM: it emulates an RS-232 serial communication port over the L2CAP protocol;

- TCS BIN: it operates at bit level for defining control signal for the voice calls and for transmission of data between Bluetooth devices. It also defines procedures for the management of TCS groups;

- SDP: within the Bluetooth technology it is important because it allows to have information about the devices, the services offered and over the available services;

- AUDIO: the function of this layer is to codify the audio signals. Two techniques can be used: logPCM and CVSD and both of them provide a flux at 64 kbit/s. The logPCM is a non uniform quantization at 8 bits. In the CVSD (Continuous Variable Slope Delta Modulation) the output bit indicates if the predicted bit is greater or smaller than the value of the signal at inlet, which is a PCM one with uniform quantization.

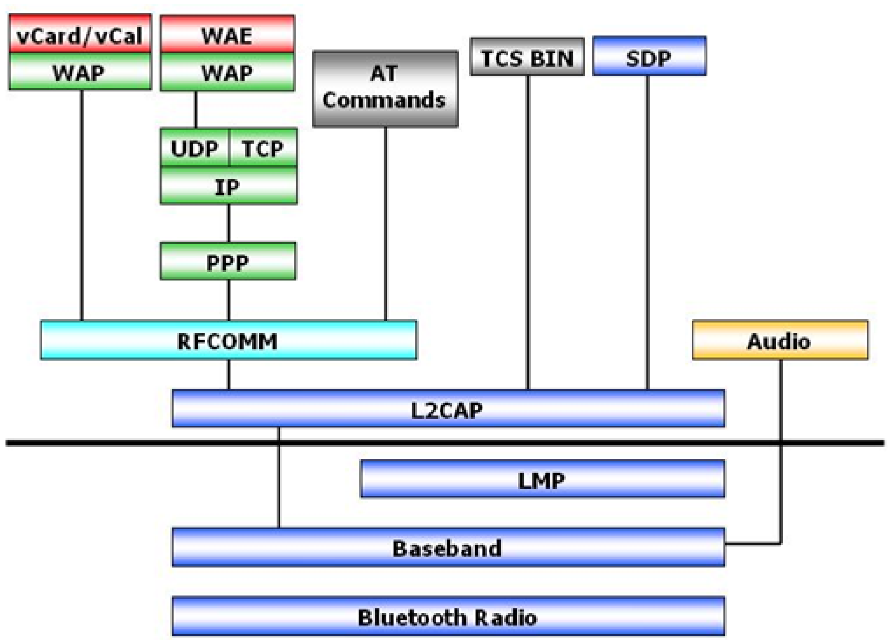


Figure 91: Scheme of a Bluetooth architecture

6 Bluetooth 5.0

6.1 Introduction

One of the first changes within the Bluetooth 5.0 technology is related to the physical layer which is called LE 2M, where LE stands for Low Energy, while 2M indicates the fact that the PHY is designed in a way to transmit a maximum of 2 Mega symbols per seconds. Since the symbols in Bluetooth transmission are bits, this means a maximum data rate of 2 Megabits/s, which makes application data rate higher.

Bluetooth 5.0 is also known having an improved transmission range and this thanks not to an improvement in the transmission power but with the introduction of a particular algorithm called Forward Error Correction code (FEC) which enables a longer communication range.

Bluetooth Low Energy can also perform connectionless communication using a procedure which is called advertising. Legacy advertising uses three channels of the 2.4 GHz ISM band which are channels 37, 38 and 39. In the Extended Advertising all 40 channels are used, providing better spectral efficiency, scalability and reduced vulnerability to reliability issues which can be caused by packet collisions in busy radio environments.

Extended Advertising allows also to improve the length of each single package that is transmitted and also allows to dela with even larger application layer payloads, because they can be fragmented and transmitted as chained packets. It also supports periodic advertising which involves advertising packet transmission which takes place at precise time intervals. This, provides a mechanism for observer devices to discover the schedule of advertisement of the advertising device and synchronize with it.

Bluetooth LE uses adaptive frequency hopping to spread communication across channels in the 2.4Ghz band. A new channel selection algorithm improves the way in which channels are selected and produces a greater degree of randomness and substantially more potential channel sequences. This improves both spectral efficiency and reliability in busy environments.

Moreover, the presence of a Slot Availability Mask (SAM) helps mitigate the common issue of interference that happens when Bluetooth radio communication are close with 4G LTE smartphone communications which use the Mobile Wireless Standard (MWS) channels.

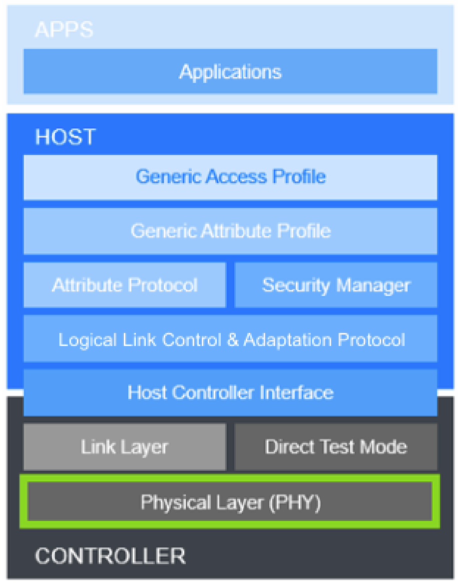


Figure 92: Architecture of Bluetooth 5.0

6.2 The LE 2M and LE Coded PHYs

In Bluetooth technology the PHY layer is responsible for two actions: encoding the bits into analog signal, called symbols, during transmission and decoding the symbols into bits during reception. The basis for the encoding of digital bits into analog signal is the modulation scheme, which in Bluetooth LE technology is the Gaussian Frequency Shift Keying (GFSK). The GFSK modulation simply consists in this: a central carrier gets shifted up by a small frequency deviation to represent a digital value of one, while it gets shifted down by the same deviation to represent the digital value of zero. The frequency shifted signal is then transmitted for a certain period of time and this constitutes a single transmitted symbol. The number of symbols that can be transmitted per unit time take the name of symbol rate and it is a property of the PHY. All the implementations of the Bluetooth LE must include a PHY called LE 1M which operates at a symbol rate of 1 mega symbol per second. At application layer, a data rate of up to approximately 800 kilobits per second is possible, when using LE 1M.

The LE 2M PHY operates at a maximum data rate of 2 Megabits/s which then becomes 2 Mega symbols per second. This is double the symbol rate of the mandatory LE 1M PHY. Obviously, for the same amount of data to transmit, an improved data rate allows to half the time of transmission and this represents a significant benefit in improved spectral efficiency. At application layer, using the LE 2M a data rate of 1,4 megabits/s is possible; obviously the speed depends on packet scheduling and on other parameters.

Normally, Bluetooth connection is used whenever it is necessary to send small amounts of data and in an occasional way. Anyway, recently there's an increasing demand on using such technology for a more frequent and regular data sending, even of packets of larger size. Firmware updates are fundamental because they allow to deliver new functionalities, fix bugs and improve the safety of the technology and so the security of the communications. Being able to perform and complete a firmware update over the air, in a quick way, helps keep the device's firmware always up to date. Generally, consumers are reluctant to update the firmware, especially if the previous experiences have been of very long installations. User experience and human behavior are as much a consideration in security as are the technical aspects.

Recently there has been a rise in the usage of devices that act as buffered sensors, especially in fields like Lifestyle Analysis and Transportation, where such devices, over several days of usage, collect a great amount of data and then they send all of them to another device, like smartphone or laptop where post-processing is going to be performed.

The original LE 1M Bluetooth has a larger range than the believed one and this has been verified with simple tests where a simple Bluetooth system MCU, a smartphone and a transmitter have been used. From such test, performed also in suboptimal environment with obstacles, a maximum range of 350 m has been achieved. There are also datasheets where it's stated that a range of 500 m can also be achieved.

Given the fact that the LE 1M PHY has a remarkably healthy range for a low power wireless communication technology, why is it necessary to increase more? Well, there are many use cases where it can be useful, like automotive ones, or home appliances.

The great characteristics of the LE 2M Bluetooth is the improved range of communication without acting on the transmission power, which literally remains the same of the 1M. But before understanding how this has been possible, it is important to understand what is meant for communication range in the field of wireless communication. In fact, communication range is not intended as the maximum distance at which the electromagnetic signal of the message can be detected, but it is intended as the maximum distance at which the message can be received and decoded correctly. A decoding error happens when at receiver side one or more bits do not coincide with the ones at transmitter side, so transmitted zero, decoded at receiver as one represents an error.

So, the receiver has the work to correctly decode the transmitted analog signal into a digital number, but it has also to deal with the naturally present background noise which affects the transmitted signal. The receiver must be able to properly filter out the noise and extract the useful signal and decode it. If the level of strength of the background noise is very close to the one of the transmitted signal, the receiver will struggle on correctly performing the decoding and probably an error will occur. A parameter that is very useful from this point of view is called SNR (Signal to Noise Ratio). A high SNR means that the strength of the signal is much higher than the background noise and so it will be decoded correctly.

It is possible to quantify the error occurring by using another parameter which is the Bit Error Rate (BER). The BER is the probability that a transmitted bit will be incorrectly decoded by the receiver. Generally, the Bluetooth Core Specification defines a BER of 0.1 % as the limit which is permitted. So, it is clear that increasing the transmission range, without increasing the transmission power and keeping the level of BER below 0.1% has been very challenging.

For what concerns errors that can occur during communication, there are basically two main approaches that can be used: the first is to perform the error detection and the second is to use the error correction. The error detection historically is the most used, in fact systems of detection errors have been used since the existence of paper and magnetic tape. Typically, Bluetooth systems use a particular type of error detection method called Cyclic Redundacy Check (CRC). The CRC consists in 24 bit elaborated by the transmitter, calculated from the message that it is sending. In the meanwhile, the receiver, while receiving the message, calculates its own CRC and then confronts it with the transmitter's one. If they are the same there are no errors, if they are different, it means that an error has occurred during communication.

Generally, when an error is detected, it is possible to do two things: or the communication gets completely aborted, or it can be restarted again as soon as the channel gets free.

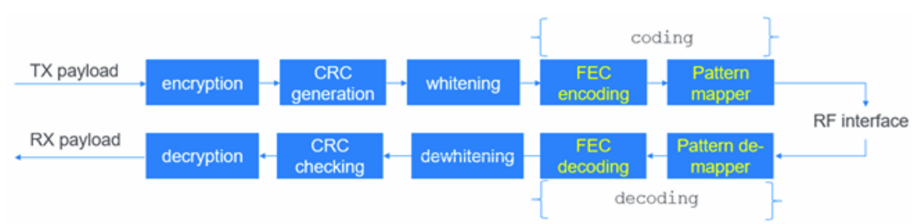


Figure 93: How works the FEC algorithm

Together with errors detection there's also errors correction which has the main advantage to avoid the retransmission of data packages. Generally, Bluetooth LE 1M and 2 M do not use error correction algorithms, but the LE with coded PHY uses it and this allows us to improve the range of communication without improving the transmission power, obviously at the condition to have a low

SNR. How does it work? Redundant bits are added to the transmitted packets, whose sole purpose is to support the application of the FEC algorithm and to allow the determination of the correct value that erroneous bits should have. The process adds two stages to the bit stream process in Bluetooth LE.

FEC encoding uses a convolutional encoder which produces two bits for each single bit transmitted by using the following generator polynomials:

$$G_0(x) = 1 + x + x^2 + x^3$$

$$G_1(x) = 1 + x^2 + x^3$$

Figure 94: FEC encoding

The LE Coded PHY can use two different coding schemes which are called respecitvelly S=2 and S=8. Both are produced by using a pattern mapper which converts each single FEC bit into a P symbol. In case of S=2 the P symbol is exactly equal to the FEC bit, instead for S=8 the P symbol is a set of four bits:

Input (from FEC Encoder)	**Output with S=2**	**Output with S=8**
0	0	0011
1	1	1100

Figure 95: Two different types of FEC coding

With S = 2, range will be approximately doubled, whilst with S = 8 it will be approximately quadrupled. As drawback, this technique produces a reduction of the bit rate at application layer.
The Hosst Controller Interface (HCI) has several commands relating to the PHY which can be invoked by the host. The HCI_LE_Set_Default_PHY command allows the host to indicate which PHY or PHYs it wants to use for Tx, Rx or both of them. With the command HCI_LE_Set_PHY the host, while transmitting or receiving, can dynamically change the type of PHY that it is using. In this way it is possible to choose the modality that allows the higher data rate when it is necessary to have an high speed of transmission, or to use the long range setup. All of this is possible by using the API which exploits the new HCI command. The host can also understand what PHY the controller is using for a particular connection both for TX and RX, using the HCI_LE_Read_PHY command.

	LE 1M	LE Coded S=2	LE Coded S=8	LE 2M
Symbol Rate	1 Ms/s	1 Ms/s	1 Ms/s	2 Ms/s
Protocol Data Rate	1 Mbit/s	500 Kbit/s	125 Kbit/s	2 Mbit/s
Approximate Max. Application Data Rate	800 kbps	400 kbps	100 kbps	1400 kbps
Error Detection	CRC	CRC	CRC	CRC
Error Correction	NONE	FEC	FEC	NONE
Range Multiplier (approx.)	1	2	4	0.8
Requirement	Mandatory	Optional	Optional	Optional

Figure 96: Differences in performances between different Bluetooth 5.0 protocols

Term	Definition
Symbol Rate	The rate at which analog symbols are transmitted at the physical layer.
Protocol Data Rate	The transmission rate of bits relating to Bluetooth protocol data units (PDUs) including their application data payload but excluding FEC data which is included in packets when the LE Coded PHY is in use.
Approximate Max. Application Data Rate	An approximate maximum rate at which application data can be communicated between applications on connected devices. Application data is transported in the payload part of various PDUs with the remainder of the protocol data rate being consumed by Bluetooth protocol data.

Figure 97: Definitions

6.3 Extended Advertising

Legacy advertising is based on the transmission of 37 octets, 8 of them are of advertising and the remaining 31 contain the payload. Advertising packets are transmitted within 3 channels of the 40 channels used by Bluetooth system within the 2.4 GHz ISM band and they are channel 37, 38 and 39.

The Bluetooth Core Specification Version 5.0 introduced some major changes on how advertising may be performed. Eight new PDUs relating to advertising, scanning, and connecting have been added and new procedures defined. Collectivelly this new set of advertising capabilities are known as extended advertising. The extended advertising allows a much larger amount of data to be broadcasted, advertising to be performed at a deterministic schedule and also allows to use multiple sets of advertising, depending on what has to be transmitted. There are also significant improvements regarding duty cycle and contention.

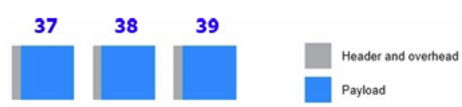


Figure 98: The three primary advertising channels

The extended advertising uses all the forty channels, in particular channels from 0 to 36 are going to do the major lifting of data transmission, while channels from 37 to 39 are carrying less than the general-purpose ones. With advertising data using all available channels, and only small headers using the primary channels, there will be less problems of contention on those channels.

Moreover, legacy advertising has the problem of transmitting the same payload up to three times on three different channels. Instead, extended advertising transmits payload data once only, with small headers referencing it from the primary channels. The total amount of data is less and so the duty cycle has been reduced.

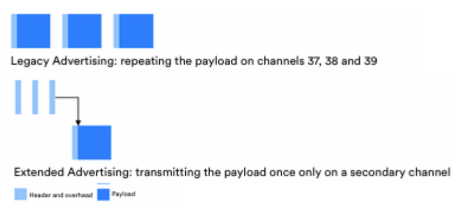


Figure 99: Extended Advertisement

Extended advertising allows to extended the lengths of the advertising packets to 255 packets, this thanks to the fact that it is possible to use also the remaining 37 general purpose channels, from 0 to 36. When performing extended advertising only header data is transmitted on primary channels 37, 38 and 39. This includes a field called AuxPtr. It references an associated auxiliary packet containing the payload which will be transmitted on a general-purpose channel. The AuxPtr contains the number of the auxiliary channel so that the receiver can easily find it.

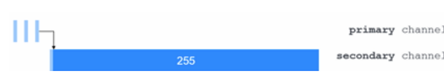


Figure 100: Extended advertisement of large packets

Legacy Advertising does not make a formal provision of the type of advertising to make and of the parameters to vary. Instead, extended advertising includes a mechanism that allows to have a set of distinct type of advertisings. The advertising sets have an ID that allows to recognize the type and its own parameters like the advertising interval and the PDU type to be used. The scheduling of the type of set to send falls in the Link Layer and makes this more power efficient instead of being in the Host Controller.

In Advertising there's always a certain degree of randomness in the transmission of the advertisement, and this thanks to the introduction of a delay that goes between 0 and 10 ms, deliberately inserted in the scheduling of the advertising events. This technique helps with avoiding persistent packet collisions. In legacy advertising this is the only way in which collisions can be avoided.

Within the Bluetooth Core Specification 5.0. there's the possibility to perform deterministic advertising and the observer devices can synchronize their scanning for packets with the schedule of the advertising device. This new technique takes the name of periodic advertisement and it makes use of the general-purpose channels. For the observer devices, the periodic advertisement makes possible to have a more power efficient way to perform the scanning and, at the same time, paves the way for the usage of Bluetooth LE in connectionless scenarios, such as broadcast audio applications.

The Generic Access Profile (GAP) now defines a synchronizable mode and a non-synchronizable mode. When operating in synchronizable mode, a Periodic Advertising Synchronization Establishment procedure gets defined.

The Periodic Advertisement introduces a new header called SyncInfo which contains information about the timing and the offset. Periodic advertisement uses a new PDU called AUX_SYNC_IND.

Further new introduction done with the Bluetooth Core Specifications 5.0. is the reduced time for Advertising Intervals, that goes from 100ms to 20 ms for non-connectable devices. This allows a higher duty cycle and will be of benefit for a fast recognition and response to advertising packets from devices like beacons.

6.4 Slot Availability Mask

Bluetooth technology uses the 2.4 GHz ISM band which is the same used for cellular communication. This can create problems of interference between Bluetooth devices and smartphones, if they are within the PAN. The set of issues relating to the inclusion of multiple radios in the same device is known as collocation. Generally, to avoid these problems of interferences the solution is to use the so-called SAM which stands for Slot Availability Map. This MAP is shared between Bluetooth devices and MWS devices, so that they can transmit and receive without any problems. The idea is the following: Bluetooth device cannot transmit during MWS uplink periods and cannot receive during MWS downlink periods.

	Legacy Advertising	Extended Advertising	
Max. host advertising data size	31 bytes	1,650 bytes	Extended Advertising supports fragmentation which enables a 50x larger maximum host advertising data size to be supported.
Max. host advertising data per packet	31 bytes	254 bytes	Extended Advertising PDUs use the Common Extended Advertising Payload Format which supports an 8x larger advertising data field.
TX channels	37,38,39	0-39	Extended Advertising uses the 37 general-purpose channels as secondary advertising channels. The ADV_EXT_IND PDU type may only be transmitted on the primary advertising channels (37, 38, 39) however.

Figure 101: Differences between legacy and extended advertisements

Bluetooth Slot	C	P	C	P	C	P	C		C	P	C	P
Can Transmit	✕	✕	✓	✓	✓	✕	✕		✓	✓	✓	✕
Can Receive	✓	✕	✕	✕	✕	✓	✓		✓	✓	✓	✓
Type Code	2	0	1	1	1	2	2		3	3	3	2

Figure 102: Example of usage of channel in environments with Bluetooth and MWS devices

Slot Type Code	Meaning
0	This slot is not available for either transmission or reception
1	This slot is available for transmission but not reception
2	This slot is available for reception but not transmission
3	This slot is available for both transmission and reception

Figure 103: Meaning of the codes

6.5 Improved Frequency Hopping

The original Bluetooth LE uses the so-called Adaptive Frequency Hopping (AFH) algorithm which randomly selects the available channels within which transmission and reception can happen. The switching of the available channels happens frequently, so span the entire communication over a large number of channels, decreasing the risk of collisions inside a very congested radio environment. Anyway, the original algorithm had the problem of providing only 12 channels within which it was possible to perform the frequency hopping and this solution was not so optimal for some application, like the audio transmission.

The new channel selection algorithm (CSA#2) offers a new sequence of selection of channels, which happens in a pseudo-random way, and this offers the possibility to improve the number of channel combinations. CSA#2 can be used in both connection-oriented applications and also for advertising. This solution offers the possibility of drastically reducing the possibility of collisions.

7 Future development: the Bluetooth transmitter

The Bluetooth transmitter that could be used for the following thesis project is the Seeed Studio XIAO ESP32C3 which is equipped with a highly integrated ESP32-C3 chip which is built around a 32 bit RISC-V chip processor with a four-stage pipeline that operates at up to 160 MHz.

The chip has integrated a 2.4 GHz Wi-Fi subsystem which means that it supports the Stationary mode, the softAP mode and also the promiscuous mode, for multiple Wi-Fi applications. It also works in ultra-low power applications, supporting features like the Bluetooth 5 and Bluetooth mesh.

The transmitter is equipped with 400 kB SRAM (Static RAM) and 4 MB Flash that allows an improved programming space, bringing more possibilities for the IoT control scenarios. The transmitter has also an additional external antenna to improve the strength of the signal for wireless applications. There are 11 digital I/O that can be used as PWM pins and 4 analog i/o that can be used as ADC pins. It supports UART, IIC, and SPI serial communication ports. Utilizing its small and exquisite hardware design and the powerful onboard chip, programming by Arduino IDE, it will offer more ability to wearable and portable devices or other applications.

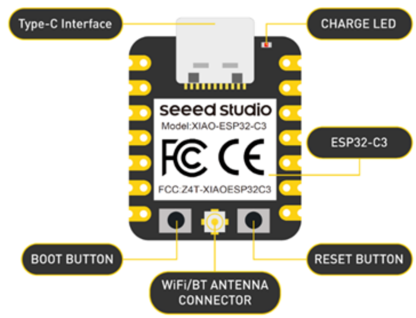


Figure 104: SEEED XIAO ESP32C3

The idea is to use the Arduino IDE for developing a software with which it is possible to monitor the state of the battery, by printing the values of voltage and temperature. Such parameters can be obtained in this way: the voltage of a parallel can be measured by directly connecting the parallel of interest to one of the three analog I/O of the SEEED XIAO ESP32C3 (A0, A1 and A2); instead, the temperature can be measured through an external temperature sensor, like a DHT 11, that gives an analog signal that should be provided to one of the three analog ports of the transmitter. Another programming language that can be used with such transmitter is the microPython.

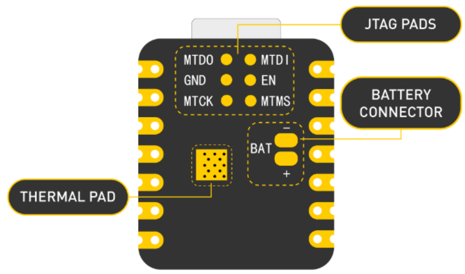


Figure 105: SEEED XIAO ESP32C3 back

It's clear that such transmitter can not handle batteries like the one used on board hybrid and electric vehicles, but smaller ones, like batteries for electric scooters, electric bikes and torches. Another important limitation, that can be easily handled, is the limited voltage that can be sensed, in fact the SEEED XIAO ESP32C3 is able to measure a voltage that goes from 0 V to 2.5 V. So, supposing I want to measure the voltage of a parallel of the 3s3p, knowing that the nominal value is of 3.6 V, I need to develop a simple voltage divider and then on the Arduino IDE it is possible to adapt the voltage sensed at the output of the divider with the actual one. The board can be power-supplied through the USB port of a laptop, or in this application can be directly supplied by the battery itslef, and this will have a certain impact on the SoC usage.

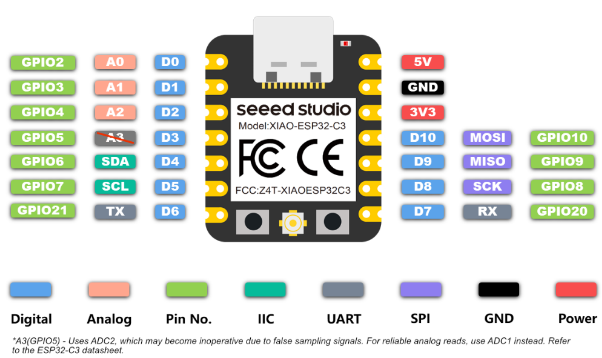


Figure 106: Scheme of pins of the SEEED XIAO ESP32C3

From the picture above it is possible to notice also the presence of two power pins and of three strapping pins.

Power Pins

- **5V**: This is the 5 V out from the USB port. It can be also used as voltage input but it is needed the usage of a diode like schottky, signal, power, between the external power source and the pin with anode to battery, cathode to 5 V pin.

- **3V3**: This is the regulated output from the onboard regulator and a current of 700 mA can be drawn from it.

- **GND**: Power/data/signal ground

Strapping pins

From the SEEED XIAO ESP32C3 datasheet, pins **GPIO2**, **GPIO8** and **GPIO9** are Strapping Pins, the high and low level configurations of such pins can allow the chip to enter into different boot modes. Please, pay attention to this point, when you use these pins, otherwise it may prevent the XIAO from uploading or executing the program all the time.

Booting Mode [1]			
Pin	Default	SPI Boot	Download Boot
GPIO2	N/A	1	1
GPIO8	N/A	Don't care	1
GPIO9	Internal weak pull-up	1	0
Enabling/Disabling ROM Messages Print in SPI Boot Mode			
Pin	Default	Functionality	
GPIO8	N/A	When the value of eFuse field EFUSE_UART_PRINT_CONTROL is 0 (default), print is enabled and not controlled by GPIO8. 1, if GPIO8 is 0, print is enabled; if GPIO8 is 1, it is disabled. 2, if GPIO8 is 0, print is disabled; if GPIO8 is 1, it is enabled. 3, print is disabled and not controlled by GPIO8.	

[1] The strapping combination of GPIO8 = 0 and GPIO9 = 0 is invalid and will trigger unexpected behavior.

Figure 107: Strapping pins of the SEEED XIAO ESP32C3

7.1 Example of battery status monitoring

For monitoring the status of the battery it is necessary to directly measure only two parameters: voltage and temperature. For what concerns the voltage, since the maximum value that can be measured by the SEEED XIAO ESP32C3 is 2.5 V, in case it is necessary to monitor the state of a battery with an higher nominal voltage, a voltage divider must be used. Such divider can be easily created by using two resistors with known resistance, connected in series to the battery and the output of such divider needs to be connected to one of the analog ports.

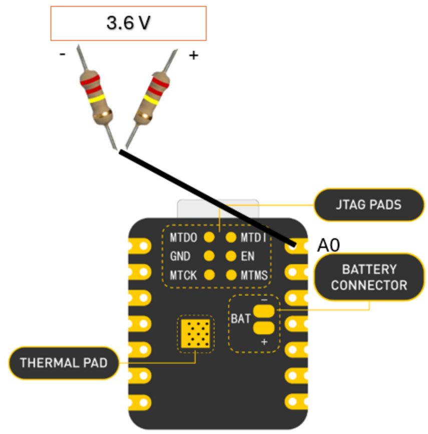


Figure 108: Connection of a parallel of the 3s3p to the SEEED XIAO ESP32C3

The voltage divider made up by two equal resistors, causes to half the voltage that is sensed at the analog pin A0 of the ESP32C3. So, by writing a very simple script, it is possible to print the value of the sensed voltage:

```
void setup() {
  Serial.begin(115200); // defining the baud rate at input port
  pinMode(A0,INPUT); // initializing pin A0 as INPUT
}

void loop() {

  uint32_t Vbatt = 0;
  float ibattf = 4.9/2; // imposing C/2 discharge
  float Zbatt = 0.004667 // internal impedence of the parallel in Ohm

  for(int i = 0; i<16; i++){

    Vbatt = Vbatt + analogReadMilliVolts(A0); // ADC conversion
    with correction
  }

  float Vbattf = 2*Vbatt/1000/16; // attenuation ratio

 // Printing voltage
  Serial.println("Voltage: ");
  Serial.println(Vbattf);
  Serial.println(" V");
```

```
// Printing current
  Serial.println("Current: ");
  Serial.println(ibattf);
  Serial.println(" A");

  delay(1000);

}
```

In the script, the value of the current is supposed to be known, because the idea is to test the battery pack with a cycler, with which it is possible to impose both discharge and charge rate and usually these tests are done with an imposed rate equal to C/2.
For what concerns the temperature, as said before, it is possible to connect to another analog input, like the A1, the output of an external temperature sensor,like a DHT 11. In this case a library, that can be easily implemented, it is necessary, in order to properly get the readings of the temperature sensor. Let's

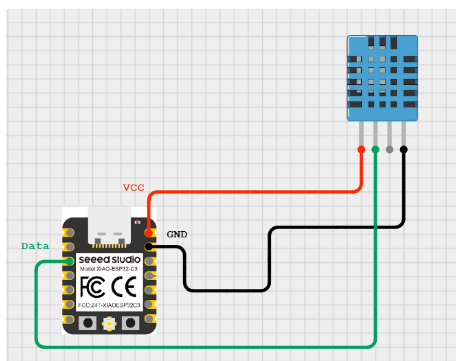


Figure 109: Connection of DHT 11 sensor and ESP32C3

give a look to the complete script, that allows also to read and print the value of the external temperature and to establish a Bluetooth connection between the SEEED XIAO ESP32C3 and a generic device equipped with Bluetooth, positioned in proximity, like a smartphone or a laptop.

```
#include "DHT.h" // including the library for DHT sensor
#define DHTPIN D6
#define DHTTYPE DHT11
DHT dht(DHTPIN, DHTTYPE);

#include <BLEDevice.h>
#include <BLEServer.h>
#include <BLEUtils.h>
```

```
#include <BLE2902.h>

BLEServer* pServer = NULL;
BLECharacteristic* pCharacteristic = NULL;
BLEDescriptor *pDescr;
BLE2902 *pBLE2902;

bool deviceConnected = false;
bool oldDeviceConnected = false;
uint32_t value = 0;


#define SERVICE_UUID        "4fafc201-1fb5-459e-8fcc-c5c9c331914b"
#define CHARACTERISTIC_UUID "beb5483e-36e1-4688-b7f5-ea07361b26a8"

class MyServerCallbacks: public BLEServerCallbacks {
    void onConnect(BLEServer* pServer) {
      deviceConnected = true;
    };

    void onDisconnect(BLEServer* pServer) {
      deviceConnected = false;
    }
};

void setup() {
  Serial.begin(115200);

  // Create the BLE Device
  BLEDevice::init("ESP32");

  // Create the BLE Server
  pServer = BLEDevice::createServer();
  pServer->setCallbacks(new MyServerCallbacks());

  // Create the BLE Service
  BLEService *pService = pServer->createService(SERVICE_UUID);

  // Create a BLE Characteristic
  pCharacteristic = pService->createCharacteristic(
                      CHARACTERISTIC_UUID,
                      BLECharacteristic::PROPERTY_READ
                    );

  // Create a BLE Descriptor
```

```
  pDescr = new BLEDescriptor((uint16_t)0x2901);
  pDescr->setValue("A very interesting variable");
  pCharacteristic->addDescriptor(pDescr);

  pBLE2902 = new BLE2902();
  pBLE2902->setNotifications(true);
  pCharacteristic->addDescriptor(pBLE2902);

  // Start the service
  pService->start();

  // Start advertising
  BLEAdvertising *pAdvertising = BLEDevice::getAdvertising();
  pAdvertising->addServiceUUID(SERVICE_UUID);
  pAdvertising->setScanResponse(false);
  pAdvertising->setMinPreferred(0x0);  // set value to 0x00
  to not advertise this parameter
  BLEDevice::startAdvertising();
  Serial.println("Waiting a client connection to notify...");
}

void loop() {
    // notify changed value
    if (deviceConnected) {
        uint32_t Vbatt = 0;
        float ibattf = 4.9/2; // imposing C/2 discharge
        float temp = dht.readTemperature(); // reading the temperature

        // Updating Modbus registers
        mb.Hreg(0, temp*10); // temperature multiplied
        by 10 to remove first float

        mb.task(); // Handle Modbus communication

        for(int i = 0; i<16; i++) {

            Vbatt = Vbatt + analogReadMilliVolts(A0);
            // ADC conversions with correction
        }

        float Vbattf = 2*Vbatt/1000/16; // attenuation ratio
        pCharacteristic->setValue(Vbattf);
        pCharacteristic->notify();
        pCharacteristic->setValue(temp);
        pCharacteristic->notify();
```

```
        delay(1000);
    }
    // disconnecting
    if (!deviceConnected && oldDeviceConnected) {
        delay(500); // give the bluetooth stack the chance
        to get things ready
        pServer->startAdvertising(); // restart advertising
        Serial.println("start advertising");
        oldDeviceConnected = deviceConnected;
    }
    // connecting
    if (deviceConnected && !oldDeviceConnected) {
        // do stuff here on connecting
        oldDeviceConnected = deviceConnected;
    }
}
```

Looking the code, at the beginning the library for the DHT11 sensor is defined and the digital pin D6 is defined as input. Then the packets for establishing the Bluetooth recognition,scanning and connection of the SEEED XIAO ESP32C3 are included. At this point the code that is wirtten has the main function to make work the SEEED XIAO ESP32C3 as a Bluetooth server, which can scan any Bluetooth device nearby, or it can be scanned and establish a connection. For Android smartphone there's an app, called LightBlue, which allows to recognize the ESP32C3 with the given name of "MyESP32" and connect to it. For what concerns the current, supposing to not knowing the rate of discharge/charge, it can be measured by using a current sensor, which output is going to be connected to one of the pins of the transmitter.

In this way, the main code for the battery monitoring gets written inside the void loop and then, through function println(), it is possible to print the results and with delay() the user can simply imposed the time period of refresh of the showed data.

Stil acting on the code, it is possible to evaluate also the SoC of the parallel just by implementing the Coulomb Counting algorithm. Remember that:

$$SoC(t) = SoC(t-1) + (I(t)/Qn) * \Delta T$$

So, supposing that SoC at t = 0 is 100 %, knowing the current flowing through the parallel, it is possible, through a for or a while cycle, to continuously update the value of the state of charge. For example, considering to use the while cycle, it is possible to impose as condition of end of updating the moment in which the SoC is at 20 % and then supposing to have an electronic contactor that can be managed by the ESP32C3, it is possible to command, at this condition, the end of the battery discharge. As already said, the Coulomb counting algorithm, despite its simplicity, has the problem to not take care about the cells aging phenomenon, since it does not consider the aging parameters.

Let's give a look to the part of code that must be included within the void loop(), inside the if when Bluetooth is connected, to implement the Coulomb Counting:

```
float Qn = 4.9; // SAMSUNG 21700-50G capacity
float SOC_prev = 1; // supposing to start with battery
                 initially fully charged
float deltaT = 0.5 ; // common pooling period of the cell

// Implementing the Coulomb Counting method
while (SOC >= 0.2) {
    float SOC = SOC_prev + (Ibattf/Qn)*deltaT;
    SOC_prev = SOC;
    pCharacteristic->setValue(SOC);
    pCharacteristic->notify();
}
```

Now, supposing the battery to monitor is the 3s3p, the idea is to use other two SEEED XIAO ESP32C3 monitoring voltage, current and temperature of the other two parallels and then there will be a third one working as master. The idea is to develop a piconet made up by three slaves ESP32C3 which have the role of monitoring the status of the parallels and sent the information to the master when it requests. Then, the master will be the one that is going to sent this information to a further Bluetooth device that will act only as a monitor from which the user can read the battery status. Obviously, this is possible thanks to the usage of the Bluetooth 5.0 LE technology. A good solution is represented by the usage of the ESP-NOW communication protocol, but what is?

7.1.1 ESP-NOW communication protocol

ESP-NOW is a wireless communication protocol created by Espressif that allows to quick, direct and low-power control of smart devices, without using any router. ESP-NOW is perfect for this application since it can work with Wi-Fi, Bluetooth LE and supports many ESP chips, not only the C3, but also ESP32-S, ESP8266 and ESP32. It is perfect for sensors, remote controlling and smart-home appliances.

ESP-NOW is based on data-link layer, so it reduces of five layers of the OSI model to only one. So, in this way, data do not need to be transmitted through network layer, transport layer, session layer, presentation layer and the application layer. Another commodity is represented by the fact that the packets of data do not need any header or unpackers at each layer. This aspects leads to a quick response, causing a reduction of the delay caused by packet loss in congested network.

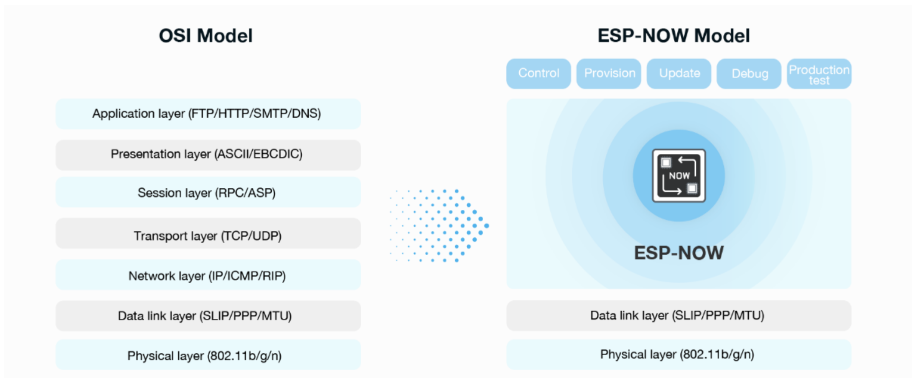


Figure 110: ESP-NOW layers

So, the advantages offered by ESP-NOW are:

- Coexists with Wi-Fi and Bluetooth LE, and supports different Espressif SoCs with Wi-Fi connectivity;
- The pairing method is fast and user-friendly and allows to "one-to-many" and "many-to-many" connections;
- Can also be used as independent protocol helping the device provisioning, debugging and firmware upgrade;
- It occupies few CPU and flash resources;
- ECDH and AES algorithms make data transmission more secure;
- The window synchronization mechanism greatly reduces power consumption;

The default data rate of the ESP-NOW protocol is of 1 Mbps. Currently, the supported version is the 1.0 and the maximum length of data package is defined as ESP_NOW_MAX_DATA_LEN. So, the v1.0 devices can receive packets which are smaller or equal to ESP_NOW_MAX_IE_DATA_LEN. For packets that have a length that is bigger than such size, they are going to be discarded.

The format of the vendor-specific action is as follows:

- Category Code: it is set to the value 127, indicating the vendor-specific category;
- **Organization Identifier**: it contains the first three bytes of the MAC Address and it is a fixed and unique identifier (0x18fe34);

```
-------------------------------------------------------------------------------------------------
MAC Header | Category Code | Organization Identifier | Random Values | Vendor Specific Content |   FCS
-------------------------------------------------------------------------------------------------
24 bytes        1 byte              3 bytes                 4 bytes            7-x bytes          4 bytes
```

Figure 111: ESP-NOW vendor-specific action frame

- **Random Value**: It is a field that is used for preventing relay attacks;
- **Vendor Specific Content**: it contains one vendor-specific element field, x = 257(250+7);

The format of the vendor-specific element frame is the following:

```
-------------------------------------------------------------------------------------------------
| Element ID | Length | Organization Identifier | Type | Reserved | Version |     Body     |
-------------------------------------------------------------------------------------------------
                                                        7~4 bits | 3~0 bits
    1 byte      1 byte            3 bytes          1 byte       1 byte          0-250 bytes
```

Figure 112: ESP-NOW vendor-specific element frame

- **Element ID**: the Element ID field is set to the value of 221, indicating the vendor-specific element;
- **Length**: it is the length of the entire frame and the maximum value is 255;
- **Organization Identifier**: it contains a unique identifier (0x18fe34) and it is the first three bytes of MAC Address applied by Espressif;
- **Type**: The Type field is set to the value(4) indicating ESP-NOW;
- **Version**: The Version field is set to the version of ESP-NOW;
- **Body**: It contains the data to be transmitted;

The MAC header is a little bit different from that of standard frames since it is connection-less. In particular, the FromDS and ToDS bits of the Frame Control field are both 0.

For what concerns the security, ESP-NOW uses the CCMP method which is regulated within the IEEE Std 802.11-2012 and it protects the vendor-specific action frame. In particular the Bluetooth device maintains a Primary Master Key(PMK) and several Local Master Keys(LMKs, each paired device has a LMK). The length of both PMK and LMK are 16 bytes.

- PMK is used for encrypting LMKs with the AES-128 algorithm. If PMK is not set, a default value will be used;

- LMK is used for encrypting the action frame of the specific-vendor with the CCMP method. If the LMK is not set, the action frame is not going to be encrypted

For initializing the ESP-NOW protocol it is possible to use the function esp_now_init(), while for deinitilizing it is possible possible to use esp_now_deinit(). Before doing the initialization it is necessary to start the Bluetooth connection, while it must be stopped after deinitializing it.

For adding a device inside the list of paired device it is necessary to call the function esp_now_add_peer(). If security is enabled, the LMK must be set. The maximum number of paired devices is 20 and the paired encryption devices should be no more than 17, the default number is 7.

When it is necessary to send something it is necessary to call the function esp_now_send() and then with the function esp_now_register_send_cb() it is possible to register the callback function. If the message is successfully received at the MAC layer it will return an ESP_NOW_SEND_SUCCESS message, otherwise it will send the ESP_NOW_SEND_FAIL. Many different reasons can lead the ESP-NOW to fail the sending of the data. For example, the non-existence of the device, or the fact that the channels used are not the same or even the loss of the frame over the air. If the data transmission ack runs out, the packages are re-transmitted again and a sequence number can also be assigned to ESP-NOW data to drop the duplicate data. Whenever there's a lot of data to be transmitted, the function esp_now_send() can be used and it allows to send less or equal than 250 bytes of data once a time. It is important to consider that too short intervals between one sending and the successive one can lead to too much disorder and improve the risk of collisions.

Instead, for receiving data packages the function esp_now_register_recv_cb() can be used.

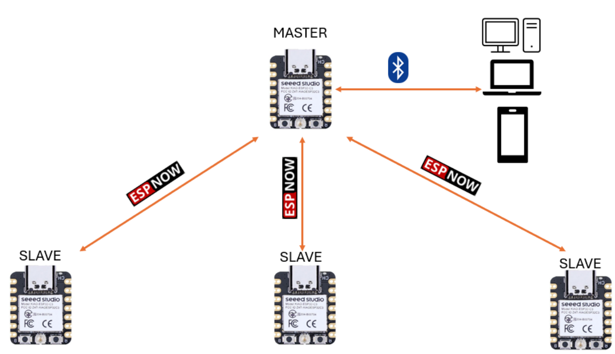


Figure 113: example of piconet used for monitoring the 3s3p remotely

7.2 Advantages of wireless monitoring over the wired one

The reason why the automotive industry is starting exploring the world of wireless solutions is mainly driven by an important voice: weight reduction of the overall system which helps reducing fuel consumption or in case of electric vehicles helps improving the traveled range, with a single battery charging process. Considering this voice, it is possible to make a confront between the weight of the BMS made up by the EMUS G1 control unit and the one made using the SEEED XIAO ESP32C3 board. The wired solution consists of such components:

WIRED SOLUTION WITH EMUS G1 BMS

- **EMUS G1 Control Unit**:
  - dimension: 97.4 x 30 x 54.5 mm;
  - weight: 94 g W/O cables, 158 with cables
- **EMUS G1 cell modules**:
  - dimension: 34 x 18 x 3.3 mm;
  - weight: 8 g
- **Current sensor**:
  - weight: 84 g (114 g with cables)

So, for a 3s3p the total weight of the system is **296 g**, while for the 13s3p **376 g**.

WIRELESS SOLUTION WITH SEEED XIAO ESP32C3

- **SEEED XIAO ESP32C3**:
  - weight: 3 g;
  - dimension: 21 x 18 mm

So, for a 3s3p the total weight of the system is **12 g**, while for 13s3p the total weight of the system is **42 g**. Looking these numbers and comparing with the wired one, for the 3s3p there's a weight saving of **284 g**, while 13s3p the weight saving of **334 g** and this is a great advantage for the wireless system. Also in terms of packaging, the wireless solution brings with it a great advantage since it allows to drastically reduce the amount of volume occupied, since there are no communication cables and the dimensions of boards and sensors are much smaller than the one offered by EMUS.

For what concerns the bit rates, the EMUS G1 Control Unit uses a USB/RS232 interface with a baud rate of **57.6 kbps**, while the interface data bits is of 8 bits. Instead, the wireless solution based on XIAO ESP32C3 using the ESP-NOW protocol for inter-board communication offers a baud rate of **214 kbps** for open environment applications while is of **555 kbps** for applications in shielded boxes. The communication between ESP32C3 master and a Bluetooth equipped device, like a smartphone, happens with a baud rate of **115.200 bps**, equivalent to **14.400 byte/s**, equivalent **14,0625 kbtye/s** and this is the typical value for applications where a wider band is required, like in some IoT applications or video-encrypted transmissions, where security is a priority.

In terms of security, there's no doubt that the wired communication system is immune from cyber-attack, since it does not allow any interface with the external environments; anyway, the wireless solution, using the ESPNOW protocol, uses, as already seen, a security system based on 128 bits security keys, developed into two levels: PMK (Primary Master Key) for accessing the network and LMKs (Local Master Keys) used for each single device within the piconet and that are used for developing the PMK, so unless a brute force approach is used and the attacker is very close from the vehicle, such system is safe.

8 Simulations carried on 3s3p

8.1 Cooling with liquid: SolidWorks CFD simulation

Before performing the future tests on laboratory with forced air cooling on the 3s3p, it is necessary to simulate, in SolidWorks environment, the behavior of the battery pack with liquid and forced air cooling.
SolidWorks is not only a CAD environment but among its many functionality allows also to perform fast and powerful CFD simulations.

To get results from the CFD simulation it is necessary to previously prepare the object that is of interest of study. In particular, it is necessary to properly confine the entire battery pack within a study volume which has a proper system of reference, then to allow to the software to calculate the available volume it is important to close all the open spaces by using the function "Lid". Once the covers at inlet and outlet have been added, it is necessary to impose to the first a mass flow of 0.0178 kg/s, which is the one supposed to be used in the real tests, and the orientation of motion of such flow, while at the outlet it is just necessary to impose the environmental pressure of 101325 Pa, so that the liquid can automatically flow, due to a natural difference of pressure from the inlet towards the outlet.

Before running the simulations, it is necessary to define the characteristics of the liquid that is going to be used, and this can be easily done by using the set-up Wizard that is run before the very first simulation. The liquid used has the following specifications:

- Name: Engineered Fluids AmpCool;
- Density: 820 kg/m^3;
- Dynamic viscosity: 0,0164 Pa*s;
- Specific heat (Cp): 2100 J/(kg*K);
- Thermal conductivity: 0,136 W/(m*K);

8.1.1 Analysis of the flow

Once everything is set up, it is possible to lunch the CFD solver and depending how much fine is the mesh generated, the simulation can last from 10 to 30 minutes. Leaving the default dimension of mesh, it takes only 10/15 minutes to end everything. As soon as the solver has concluded to perform all the calculations, by using the post-processing tools of SolidWorks, it's easy to give a look to the results, in terms of fluid flow and flow statistics like speeds, mass and volume flow rate, pressure drops and with the graphical representation of the flow is also possible to have an immediate perception about the presence of possible points of stagnation, points of fluid recirculation and generation of

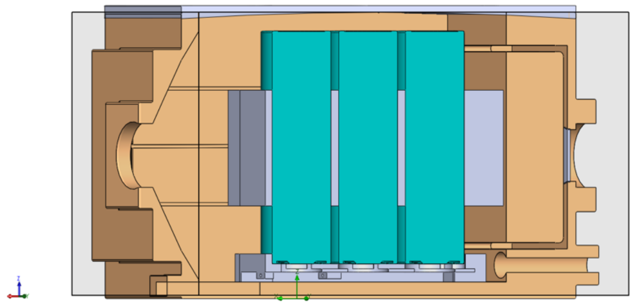


Figure 114: Section view of the entire 3s3p battery pack, with single fluid divider which allows to uniformly cool top and bottom of the cells

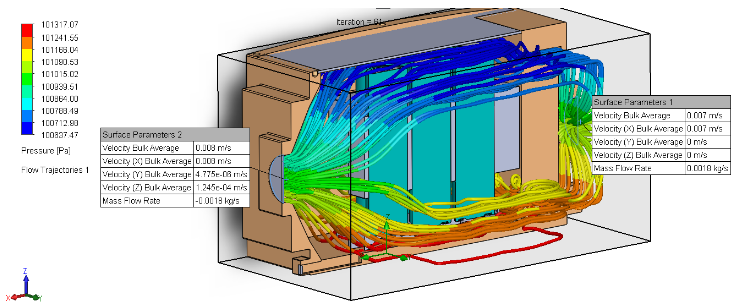


Figure 115: CFD of the cooling of top and bottom of cells

vortexes. The first CFD simulation has been carried out using a single fluid divider, positioned in the middle of the cells volume, so to emulate the cooling of both top and bottom in an equal way. Looking at figure 107 it is possible to appreciate how the flow is equally distributed on top and bottom, how it perfectly flows from the inlet to the outlet without showing any stagnation or generation of vortexes, but it perfectly follows the cylindrical shape of the cells, running towards the end and perfectly converging to the outlet.

Giving a look to the color tab, it is possible to appreciate how the pressure drop within the entire battery pack volume is very limited, in fact it goes from 101570,21 Pa of the inlet to 100634,62 Pa of the outlet and this is a numerical confirmation of what has been said before and of what the graphical representation shows: the fluid encounters no obstacles during its flow.
Looking everything from the top it can be appreciated how the fluid perfectly runs through the cells, sneaking towards the cylindrical walls and perfectly converging at the outlet. Moreover, it can be seen how the fluid covers the entire top volume in an almost homogeneous way.

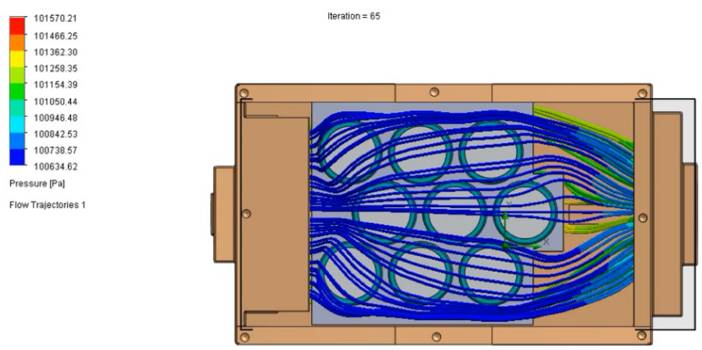


Figure 116: Top view of the CFD simulation with single divider

Then, a second test is done using two dividers this time, which are positioned in a way to leave empty the space in the middle of the cells. This layout is used to let cool down this part of the cells. To make cooling the most effective possible, the outlet of the box shaped component of the casing has been modified: instead of having the two slots on top and bottom, there's a single circular hole, through the entire volume of the component with a divergent shape which is fundamental for properly guiding and stabilizing the flow, so to avoid, once it impacts with the cell, the generation of vortexes or the recirculation of liquid.

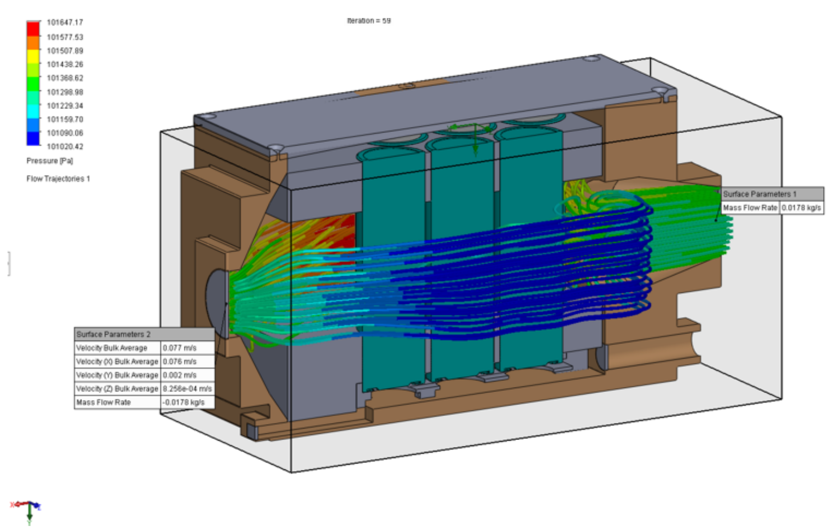


Figure 117: CFD simulation with the two dividers layout

Looking at picture 117, it is possible to appreciate how the coolant, before hitting the cells, is already stabilized in terms of velocity, pressure and orientation and then, as it impacts the cells, does not recirculate back or generate vortexes, but it perfectly follows the cylindrical shape of the batteries and converges through the outlet with the flow lines all parallel to each other. The absence of vortexes, recirculation and point of stagnation are not only witnessed by the graphic representation of the flow lines, but also by the numerical results which are observable at inlet and outlet from figure 80: the mass flow rate is the same at the two points and at the outlet it is possible to see how the speed of the flow is mainly characterized by the longitudinal x component, which is a sign of negligible turbulent motion.

8.2 Analysis of the temperature distribution

The second type of analysis is focused on checking the effectiveness of the cooling of the cells while using the battery, looking how their temperatures evolve. The cells have been tested in two different conditions: forced air cooling and forced liquid cooling. As for the CFD simulation and the CAD modeling, the software used is SolidWorks.

Before running the simulations, is necessary to choose the materials for the cells, for the bus bar mount and for the fluid dividers. In particular, for the cells, the SAMSUNG 21700-50G use a cover in aluminum, in particular aluminum 3003, while for the remaining components the material used is the PLA. This last material has been defined by the user since it was not present in the database of the software.
The characteristics of the aluminum 3003 are the following

- Elastic modulus : 6.9e+10 N/m^2
- Poisson Coefficients : 0.33
- Shear modulus : 2.7e-10 N/m^2
- Mass density : 2700 kg/m^3
- Resistance to traction : 110297000 N/m^2
- Enervation : 413613000 N/m^2
- Coefficent of thermal expansion : 2.3e-05 /K
- Thermal conductivity : 170 W/(m*K)
- Specific heat : 1000 J/(kg*K)

Instead, the characteristics of the PLA are the following:

- Elastic modulus : 3.5e+09 N/m^2

- Poisson Coefficient : 0.394
- Shear modulus : 2.4e+08 N/m^2
- Mass density : 1240 kg/m^3
- Resistance to traction : 6.134e+07 N/m^2
- Resistance to compression : 5.0 e+07 N/m^2
- Coefficient of thermal expansion : 5.7 /K
- Thermal conductivity : 0.2256 W/(m*K)
- Specific heat : 1386 J/(kg*K)

After having defined the materials of the components, it's important to define which are the surfaces which are going to be involved by the flux of coolant and then it's necessary to impose a heat flux coming out from the cells.
The values of the specific thermal power emitted by the cells are obtained from the following experimental plot:

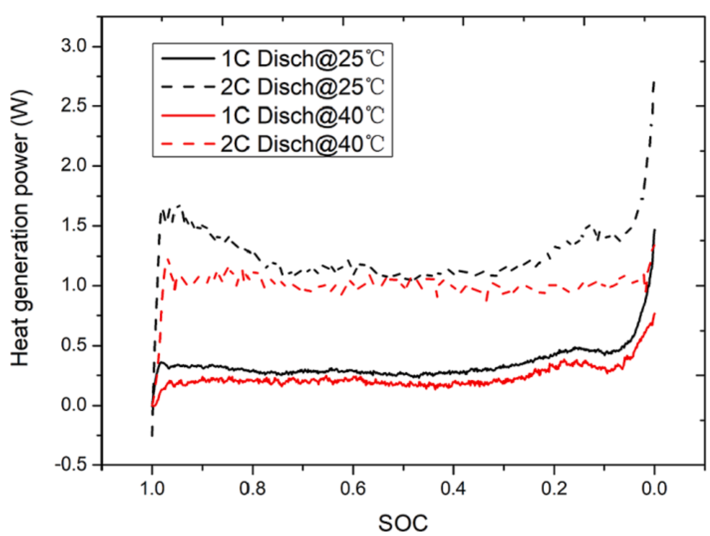


Figure 118: Thermal power emitted by SAMSUNG 21700-50G during discharge

As can be seen from the picture above, cells are tested with a two different discharge rates (1 C and 2 C) and at two different temperatures (25°C and 40 °C).

For the simulations has been decided to take into account the worst operating condition, which corresponds to the cell fully discharged. In fact, from the plot it is possible to see how as soon as the cell fully discharges, there's a peak of thermal power emitted to the outside. The flux of emission is considered coming out radially from the lateral surfaces of the cylindrical cells.

8.2.1 Forced air cooling - simulations

The first tests and simulations are carried out considering to cool down the cells with forced air. In particular, for such operating condition, the casing and fluid dividers have been removed, so the cells have been tested only with the bus bar mount. The thermal convective coefficient for forced air oscillates around 5-15 W/m^2K.

Concentrating at the moment on the simulations carried out on SolidWorks, let's give a look to the four different combinations:

- **1 C at 25°C**: As expected, among the nine cells, the one which results being the hottest is the central one, since it surrounded by other six cells, irradiating thermal energy to it.

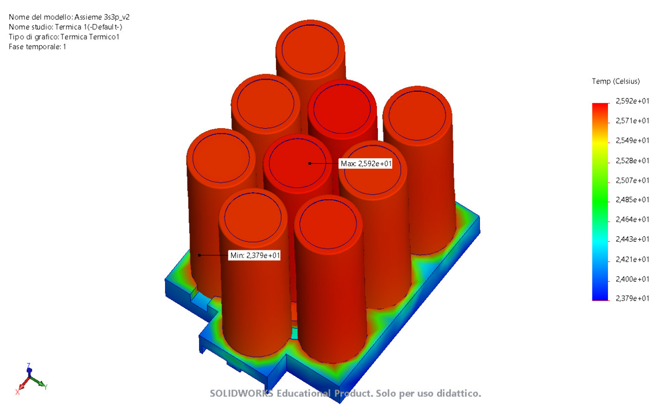


Figure 119: Thermal behavior of the pack cooled with forced air at the end of discharge: 1 C at 25°C

From figure 81, a single cell discharging with a rate of 1 C at 25°C, at the end of the discharge, emits around 1.3 W and considering that the lateral surface of the SAMSUNG 21700-50G is 0.0046 m^2, means that the specific thermal power is 282.61 W/m^2. As can be seen from the representation above, the thermal drift within the entire pack is limited: the hottest point, as said, is represented by the central cell, which is kept at a temperature of 25.92°C, while the coolest point is in the lower side of the bus bar mount, in correspondence of the last cell on the left, with a temperature of 23.79°C.

Instead, during the discharge process, the power emitted by the cells is in average around 0.8 W, which corresponds to 173,91 W/m^2, so it's expected a smaller temperature gradient within the entire volume of the pack and also a lower maximum temperature. As before, the hottest spot continues to be the middle cell with a T=24.97°C, which means that is slightly cooled respected the initial temperature.

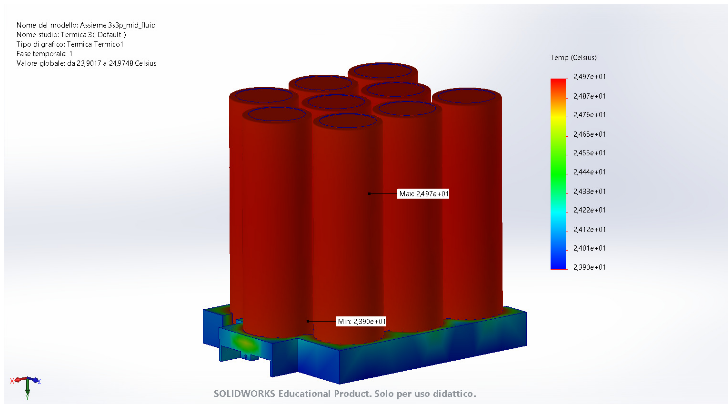


Figure 120: Thermal behavior of the pack cooled with forced air during discharge: 1 C at 25°C

- **1 C at 40°C**: At 40°C with a rate of discharge equal to 1 C, the thermal power emitted by each cell is equal to 0.70 W, which corresponds to 152.17 W/m^2. So, respect the previous case, thermal power emitted is lower, so it's reasonable to suppose a lower temperature drift within the battery pack. As usual, the hottest point is represented by the central cell, while the coolest point is again in the lower part of the bus bar mount.

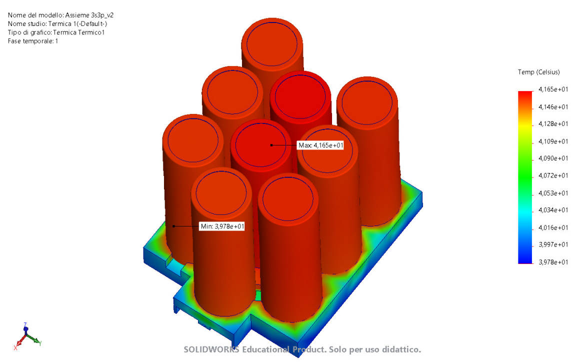


Figure 121: Forced air at the end of the discharge: 1 C at 40°C

As predicted, the thermal drift is very limited, the lowest temperature is 39.78°C, while the highest is 41.65°C. Instead, considering the cells while discharging, the average power emitted is 0.5 W, corresponding to 54.35 W/m^2.

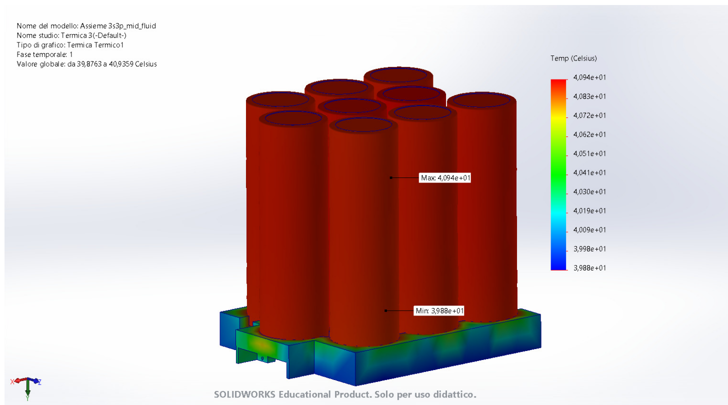


Figure 122: Thermal behavior of the cells while discharging: 1 C at 40°C

- **2 C at 25°C**: A discharge with a rate of 2 C means that the current used is twice the capacity of the cell and the time taken to get a 0 SOC is halved respect the previous cases. For sure, due to the higher current, the thermal energy emitted by the cells is greater respect when discharged with a rate equal to 1 C. In fact, from the experimental plot, the maximum thermal power, radially emitted, by a single cell is equal to 2.7 W, which is equivalent to 586.96 W/m^2, much higher than the previous cases.
  So, as a consequence is expected to have a wider temperature range within the pack and a higher value of maximum temperature.

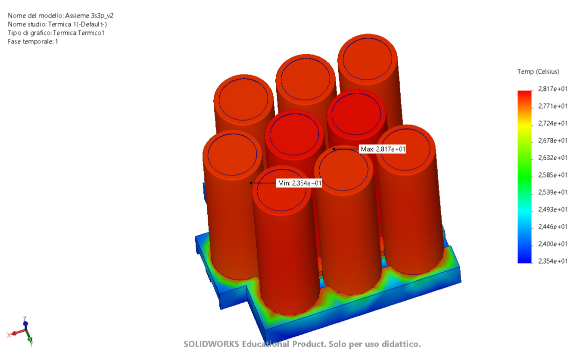


Figure 123: Thermal behavior of the cells at the end of discharging: 2 C at 25°C

As before, the maximum temperature of 28.17 °C is registered on the cell

in the middle of the pack, while the minimum temperature of 23.54°C is registered on the lower side of the bus bar mount, on the left, below the last cell.
Instead, while discharging, the average power emitted by each cell is equal to 0.725 W, which corresponds to 157.61 W/m^2. This leads to a lower temperature range within the pack and also a lower maximum temperature.

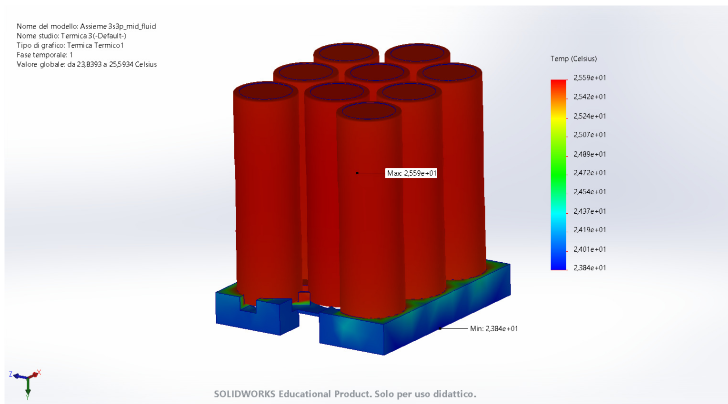


Figure 124: Thermal behavior of the cells while discharging: 2 C at 25°C

2 C at 40°C: Like for the case with a rate of discharge of 1 C, even with 2 C, from the experimental results, it's possible to notice a slight reduction in the overall thermal power emitted by a single cell during discharge. Approaching a SOC equal to 0, a cell emits a maximum thermal power around 1.2 W, equivalent to 260.87 W/m^2, which is slightly lower than the one emitted by a cell discharged with a rate of 1 C at a temperature of 25°C. The maximum temperature registered is 43.02°C, while the lowest is 39.50°C.

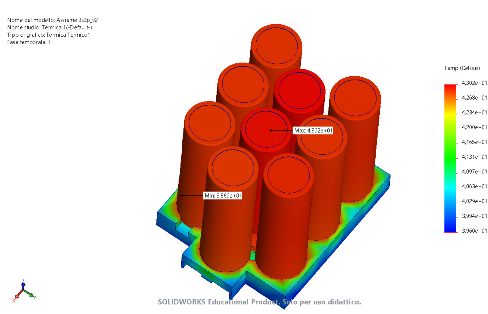


Figure 125: Thermal behavior of the cells at the end of discharge: 2 C at 40°C

Instead, while discharging the average thermal power emitted by the cells is equal to 0.75 W, corresponding to 163.04 W/m^2.

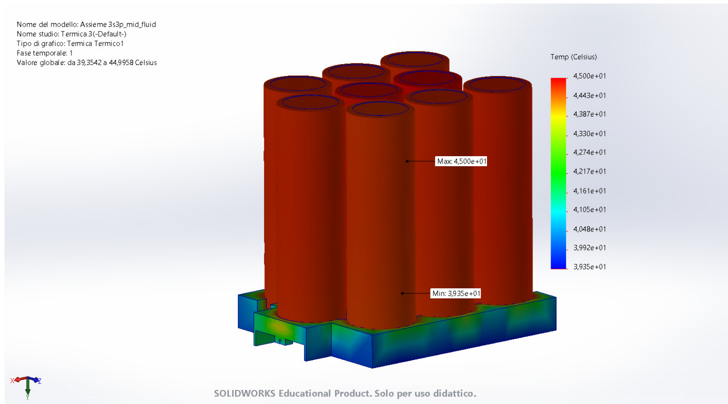


Figure 126: Thermal behavior of the cells while discharging: 2 C at 40°C

8.2.2 Liquid cooling - simulations

For what concerns the liquid cooling, only simulations on SolidWorks have been carried out. On the analysis, the casing and the lid have been omitted, so only the cells with fluid dividers and bus bar have been analyzed.

Just like for the CFD simulations carried out for analyzing the fluid flow within the casing, two different configurations have been considered: cells cooled on top and bottom with a single central fluid divider and cooling in the middle with two fluid dividers, respectively placed on top and bottom. Like for the previous analysis, done with forced air, four different conditions have been tested: discharging at 1 C and 2 C and temperatures of 25°C and 40°C. For sure, since here cooling is done with a forced liquid, the coefficient of convection will be much higher than the one of forced air. Generally, for forced eater cooling, coefficient of convection can range from 500 to 10000 W/K*m^2, while for oil it can range from 60 to 1800 W/K*m^2. So, respect the previous cases what is expected, for each operating condition, is a more homogeneous distribution of the temperature within the pack and also a final temperature lower then the initial one.

First, the case of top and bottom cooling is going to be analyzed and then the central cooling is going to be considered.

Top and bottom cooling

In this configuration, the part of the cells that are going to be directly cooled by the liquid are the top and the bottom. Since the liquid that is used for cooling is very similar to oil, in terms of physical properties, a convection coefficient of 1050 W/m*K^2 has been imposed.

- **1 C at 25°C**: In this condition each cell, at the end of discharge, which is the worst operating condition, emits a thermal power of 1.3 W, equivalent to 282.608 W/m^2.

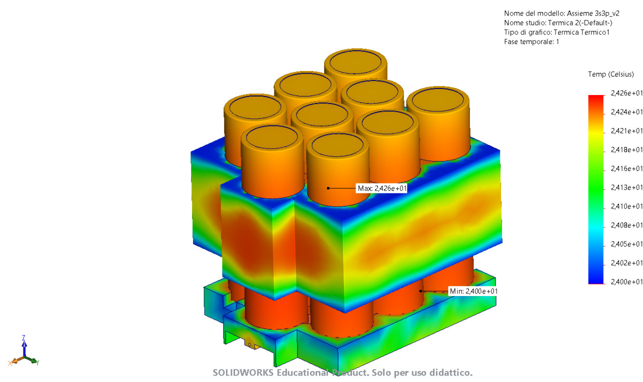


Figure 127: Top and bottom cooling with liquid: 1 C at 25°C

The temperature range is very restricted, it goes from 24°C to a maximum of 24.26°C, so in steady state conditions, the average final temperature of the battery pack is lower than the initial one, and this thanks to the higher value of convection coefficient offered by a liquid coolant. Even if the representation does not allow to properly appreciate it, the hottest point of the pack is still in the cell positioned in the middle of the pack, while the coolest point is below the bus bar mount. Looking at the temperature distribution of the fluid divider, since the fluid flow interests top and bottom, clearly the fluid passing by, touches the upper and lower faces of the fluid divider, so this explains why these surfaces are cooler than the core, which gradually heats until the center.

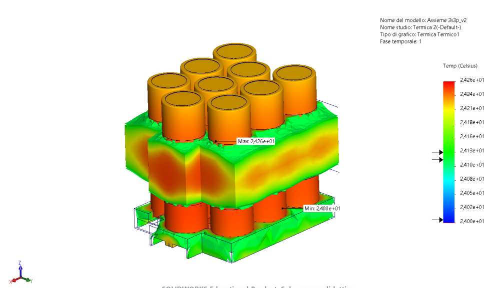


Figure 128: ISO surfaces section, top and bottom cooling with liquid: 1 C at 25°C

- **1 C at 40°C**: In this operating condition, each cell emits a radial thermal power around 0.7 W, equivalent to 152.174 W/m^2, lower than the previous case.

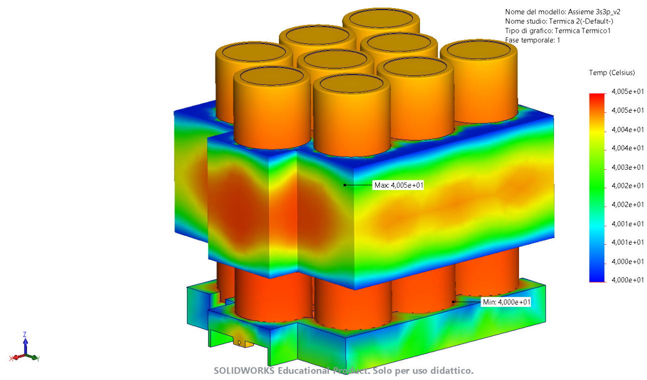


Figure 129: Top and bottom cooling with liquid: 1 C at 40°C

The maximum temperature reached is of 40.12°C, while the minimum registered is of 40.00°C. As usual, the hottest point of the pack is represented by the cell mounted in the middle, while the coolest spot is below the bus bar mount, at the inlet side. Looking at the color progress through the body of each cell, it is possible to see how moving from top to the middle the temperature gradually improves and the same happens on the lower side of the cell, even if from the picture above is not well visible, but the minimum temperature is registered in that area.

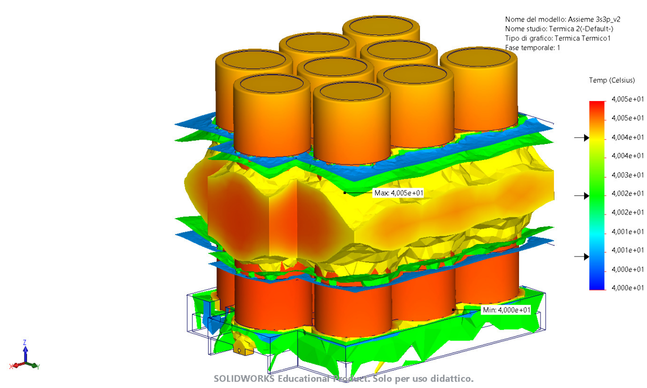


Figure 130: ISO top and bottom cooling with liquid: 1 C at 40°C

- **2 C at 25°C**: At the end of discharge, which is the worst case scenario, the cell emits a thermal power of 2.7 W, equivalent to a specific power of 586.956 W/m^2. This induce, respect the previous two cases, to have a wider temperature range within the pack.

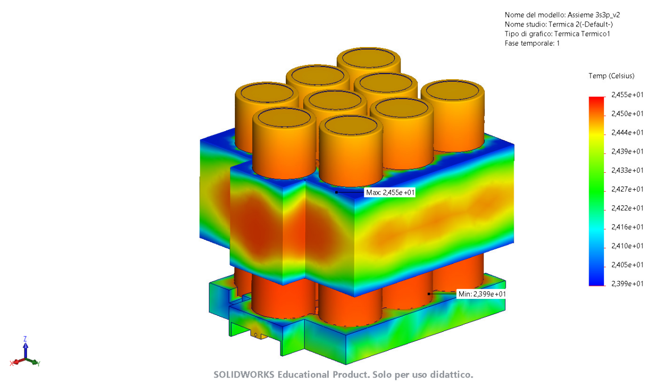


Figure 131: Top and bottom cooling with liquid: 2 C at 25°C

The picture affirms what has been said above, in fact the maximum temperature registered is of 24.55°C, while the minimum is of 23.99°C. As usual, the spots where these temperatures are detected are always the same: the middle cell and below the bus bar mount, at the inlet side. Despite the important value of specific thermal power emitted by each cell, the liquid cooling is so efficient to maintain the entire pack at an average temperature which is lower than the initial one of 25°C.

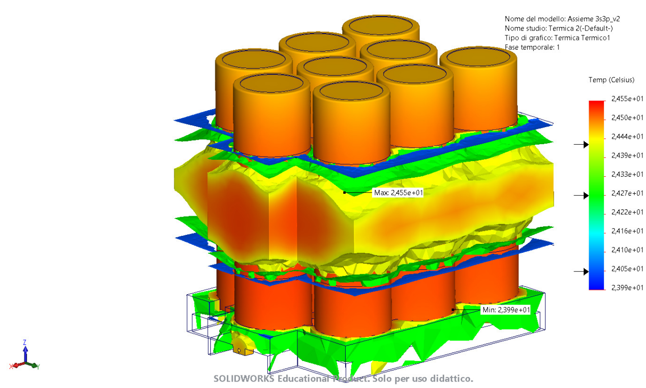


Figure 132: ISO section top and bottom cooling with liquid: 2 C at 25°C

- **2 C at 40°C**: The thermal power emitted by a single cell under this condition is equal to 1.2 W, equivalent to 260.869 W/m^2, which is not only lower than the one emitted at 25°C, but it is also slightly lower than the one emitted with a discharge rate of 1 C at 25 °C.

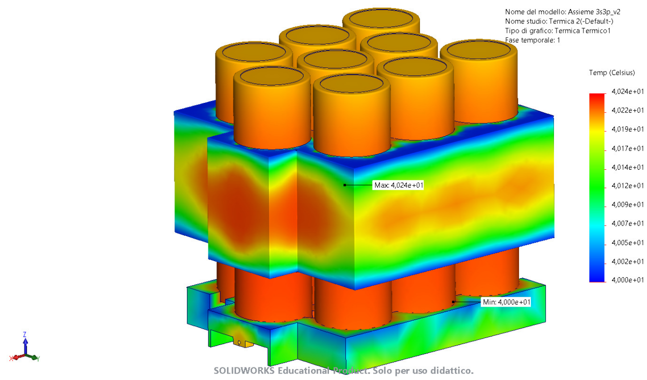


Figure 133: Top and bottom cooling with liquid: 2 C at 40°C

Respect the case 1 C at 40°C, the maximum temperature reached is slightly higher and it is equal to 40.24°C. The minimum temperature expected is of 40°C. The spots where these temperatures are registered remains always the same.

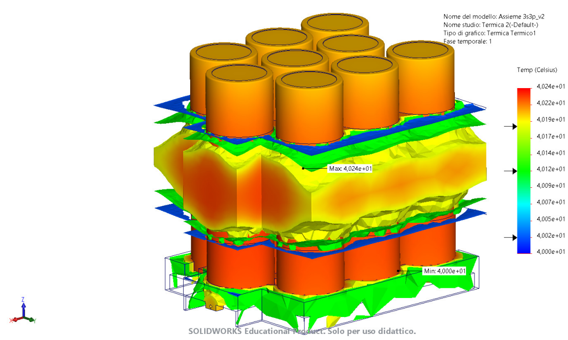


Figure 134: ISO section top and bottom cooling with liquid: 2 C at 40°C

9 Acknowledgments

At the conclusion of this thesis project I would like to express my deepest gratitude to professors Angelo Bonfitto and Vittorio Ravello for the great opportunity to work on a very interesting, multi-disciplinary and challenging project. I would like to thank Ph.Ds Saulius Pasktys, Marco Maritano and Fabio Boscarino for the continuous sustain and help throughout all these months and also a big thank goes to all the guys with which I have shared the New Energy Vehicles Joint Lab office during the whole experience, for having shared with me the knowledge and passion for what we have done.

References

[1] Fabian Rincon Vija. Enabling robust wireless communication for battery management systems in electric vehicles. Embedded Systems. Ecole nationale supérieure Mines-Télécom Atlantique, 2022.

[2] Akash Samanta and Sheldon S. Williamson. A Survey of Wireless Battery Management System: Topology, Emerging Trends, and Challenges, 2021

[3] Roman Gozdur, Tomas Przerywacz, Dariusz Bogdanski.Low Power Modular Battery Management System with a Wireless Communication Interface, 2021

[4] Hossam A. Gabbar, Ahmed M. Othman and Muhammad R. Abdussam. Review of Battery Management Systems (BMS) Development and Industrial Standards, 2021

[5] Wei Liu, Tobias Placke, K.T. Chau, Department of Electrical and Electronic Engineering, The University of Hong Kong, Pokfulam, Hong Kong Special Administrative Region of China b MEET Battery Research Center, University of Münster, Corrensstraße 46, 48149 Münster, Germany. Overview of batteries and battery management for electric vehicles, 2022

[6] Chunjing Lin, Haoran Wen, Lei Liu, Shiqiang Liu, Tianyi Ma, Bin Fan, Fang Wang, China Automotive Technology and Research Center Co., Ltd. (CATARC), Tianjin 300300, China b Harbin Institute of Technology, Harbin 150001, China c School of Chemical Engineering and Technology, Tianjin University, Tianjin 300350, China. Heat generation quantification of high-specific-energy 21700 battery cell using average and variable specific heat capacities, 2020

[7] Greg Zimmer, Sr. Product Marketing Engineer, Signal Conditioning Products Linear Technology Corporation. Wireless Battery Management Systems Highlight Industry's Drive for Higher Reliability

[8] Author: Floridia Stefano; Professor: Passerone Claudio; Supervisor: Leandro Malara. Analysis and development of Battery Management System for electric vehicles, A.A 2021/2022

[9] Pallavi Bansal, Nagaraj PR. Wireless Battery Management System for Electric Vehicles, 2019

[10] Brett Warneke, Gerd Trampitsch, Mark Lemkin, Thor Juneau, and Lance Doherty.Wireless Communication in Battery Management Systems. Cord-cutting for gen-EV, 2022

[11] Martin Wooley. Bluetooth® Core Specification Version 5.0 Feature Enhancements Bluetooth® Core Specification Version 5.0 includes several primary updates, 2021

[12] Elektromotus EMUS BMS documentation. EMUS BMS Serial Protocol, Version 2.0.12

[13] Elektromotus EMUS BMS documentation. G1 Cell Module - Small Type

[14] Elektromotus EMUS BMS documentation. Loop Style Current Sensor

[15] Elektromotus EMUS BMS documentation. G1 Control Unit

[16] SEEED XIAO Studio ESP32C3