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(Article begins on next page)

25 April 2024

This is the final peer-reviewed accepted manuscript of:

The Fabric ICT platform for managing Wireless Dynamic Charging Road lanes / Cirimele, Vincenzo; La Ganga, Alessandro; Colussi, Jacopo; DE GLORIA, Alessandro; Diana, Michela; El Sayed, Nadim; Bellotti, Francesco; Berta, Riccardo; Kobeissi, Ahmad; Guglielmi, Paolo; Ruffo, Riccardo; Khalilian, Mojtaba. - In: IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. - ISSN 0018-9545. - 69:(2020), pp. 2501-2512

The final published version is available online at:

https://dx.doi.org/10.1109/TVT.2020.2968211

The Fabric ICT platform for managing Wireless Dynamic Charging Road lanes

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Abstract—As dynamic inductive power transfer for electric vehicles is growing in relevance, it is important to analyze solutions towards its deployment and integration in the cloud-based services for electric mobility. In this paper we present an Internet-enabling platform for Electric Vehicle Supply Equipment, which features a high-level Charging Station Control Unit and a Power Electronics Controller. The platform is a middleware that controls the charging process taking into account outside world information. Tests were performed in a safe driving track, in Italy, to verify the effectiveness and robustness of the installation, for one year, for a total of 120 drive hours, under various weather conditions. Tests showed the suitability of the platform in terms of ability to authenticate and authorize a vehicle even through a remote service, sequentially control each coil in a lane, monitor the charging process, assist the driver in keeping the vehicle aligned so as to maximize the energy exchange and deliver charging session information to the cloud (e.g. for billing).

Index Terms—Dynamic inductive power transfer, electric vehicles, authentication authorization and accounting, energy billing, lane alignment.

I. INTRODUCTION

E LECTRIFICATION of road transport has become a significant trend in research and industry (e.g., [1]–[3]). Still, state of the art batteries involve high costs and low power density compared to classic fossil fuels. Also, rather long stops are needed for recharging, and battery behavior is still not very predictable during travel [4]. To date, there is a lack of infrastructure able to properly manage electric vehicle (EV) traffic and its energy and communication requirements. In the last few years, there has been a growing interest in the technology known as dynamic inductive power transfer (DIPT) as a way to cope with the limited range of batteries [5]. Various solutions for DIPT have been proposed in literature, which differ in terms of transmitting coils' shape and size [6]–[8], control techniques [9], [11], [12], communication links

[12], [13]. As DIPT for EVs is gaining relevance, literature lacks papers which analyze solutions towards its deployment in authentic contexts of use.

Operation of an Electric Vehicle Supply Equipment (EVSE) for the DIPT case involves several additional challenges beside the power transfer itself. The electric power exchanged between the electric grid and the vehicle needs to be metered for each EV charging session. Thus, EVs approaching a charging lane must be authenticated and authorized. Since several EVs may be in the proximity of the EVSE and simultaneously communicating wirelessly with the EVSE, the road-side unit should also perform proximity detection, so to identify the EV in the immediate proximity of the transmitter coil. Recognition and distinction of the EV is also important for the energy supply measurement, which can be later used for billing. Additionally, an EV driver may need reliable information about the EVSE (e.g. lane length and grid position), its status (e.g. operational or faulty), and parameters (e.g. power level, operating frequency, etc.) long before arriving in its proximity. For example, the EV navigation system might display such information, allowing the driver to decide whether to use that EVSE or not. This calls for an Internet based service. Beside information provision, many actors in the E-mobility domain will have interest in controlling the EVSE remotely. One could think of a power grid distribution system operator that needs to keep its network stable. In case many EVs want to charge on the same lane, the distribution system operator might need to set a higher limit for EVSE power delivery. A similar case is the reservation of the EVSE for a certain EV. This possibility is often desired by navigation system manufacturers, since it allows them to offer premium services to their customers.

We thus argue that an EVSE would strongly benefit from availability of an ICT platform, both for controlling in real-time the whole charging process (from vehicle access and authorization until departure) and for supporting creation of E-mobility services.

This paper describes the concepts behind the design of a novel Information and Communication Technologies (ICT) platform aimed at combining the DIPT physical control with a set of distributed services for E-mobility (i.e. mobility mainly based on the use of electric vehicles) providing a cooperation network for EVs. The platform intends to guarantee safe operations, maximize the energy exchange and support the simultaneous utilization by several vehicles. In the proposed architecture, a multiple control strategy is employed at three levels. At low level (i.e. the level of the power electronics) the

adopted control strategy is a unique feature of the proposed DIPT system. It builds on the sensor-less procedure presented for the first time by the authors in [9], and guarantees both the identification of the presence of an arriving vehicle and an effective management of its wireless charge. The robustness and the rapidity of this control allowed to perform the charge on the move without the need for simultaneously activating all the coils of the charging lane, with a consequent increase in safety and efficiency. At high level control (i.e. the level of the roadside system of the infrastructure) the presented architecture allows the recognition and distinction of each vehicle for the energy supply measurement and allows to enable the low level control only when the vehicle is in the proximity of the charging lane. At the level of the vehicle side system, a vision-based Grid Alignment Assistant System (GAAS) helps the driver to reduce the misalignment of the vehicle, with the aim of improving the charge efficiency. The combination of these three control strategies allows to achieve an effective and more efficient wireless charge, including the accounting of the energy supply.

This platform was developed in the context of the Fabric EU industrial research project and tested in road tests in a safe drive track in Italy. To the best of our knowledge, this is the first example in literature that such a complete system is presented, including experimental tests.

The remainder of the paper is organized as follows. Section II discusses the related works. Section III presents the system architecture, with the main components and their logic. Section IV presents the test site settings and the results. The final section draws the conclusions and indicates possible directions for future work.

II. STATE OF THE ART

An easier access to charging is considered a useful response to the issue of EV battery drain [14]. In general, EV traffic needs an adequate infrastructure in terms of energy management but also of communication among vehicles, the road infrastructure, and several other actors involved in this complex system. Alongside the standard plug-in systems for the recharge, there has been a growing interest in the last decades towards the wireless charge based on the inductive power transfer (IPT) technology [15], [16]. In the last years, several researchers have moved towards the so-called dynamic IPT (DIPT), aiming to take advantage of the absence of electric contacts to allow the powering of the vehicle and the recharge of the battery while the vehicle is moving. This would clearly eliminate the necessity of stops for the recharge and, in the long run, the adoption of DIPT could lead to a strong reduction in the capacity of the vehicular batteries [17]. However, while several DIPT systems have been proven by means of laboratory prototypes [18]–[20], only few of them have been really implemented and integrated in a road infrastructure. Probably the most successful of such kind of systems is the On-line electric vehicle (OLEV) developed by the Korea Advanced Institute of Science & Technology (KAIST) [21]. This DIPT system was installed to power an electric bus in the KAIST campus. Another system for public
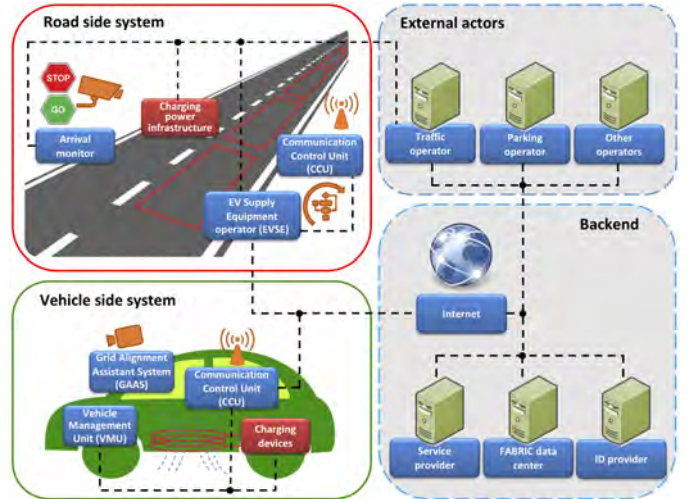

Fig. 1: High-level view of the Fabric platform and its interactions.

transports has been demonstrated by the CIRCE laboratory within the Victoria project in Spain [22].

The above systems have shown the feasibility of the concept, but also the existence of several open issues. Particularly, all the above mentioned systems focus on the electric and magnetic hardware while, the management of the charging road lane has not been considered as a fundamental part.

An important factor for energy transfer efficiency is the alignment of the EV receiver with the ground transmitter coil, so to maximize the magnetic coupling. To this end, [23] presents a system to deliver an equal amount of energy for all lateral misalignments in the range of ± 15 cm, which improves the expected value of transferred energy by more than 30%. [24] proposes an autonomous coil alignment system using fuzzy steering control based on the voltage difference between two coils installed on the front-left/front-right of the receiver coil. We have adopted a vision-based approach, developing a lane and coil grid detection module exploiting a low-cost open source hardware platform, such as Raspberry Pi.

III. SYSTEM ARCHITECTURE

In order to target the integration of the DIPT physical control with the E-mobility environment, we defined an ICT platform featuring two key innovative components: the Charging Station Control Unit (CSCU) and the Power Electronics Controller (PE Controller). The former is the high level orchestrator that coordinates the EVSE activity by making the PE control process aware of the external services and by communicating back to the cloud information about each charging session. The latter is the middleware that actually controls the charging process keeping into account all the needed factors, also from the external world. We argue that a crucial functionality of the platform is given by authentication and authorization, since identity is the key to share information between high level services and low level control.

Fig. 1 shows a high-level scheme of the Fabric architecture, highlighting the road side and the vehicle side. The back-end includes a middleware platform with functionalities for data collection, aggregation and management, and a server
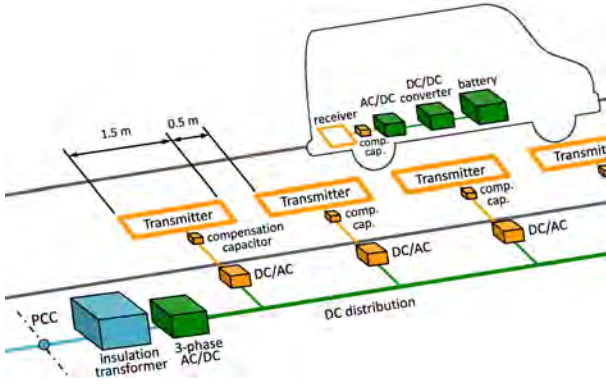
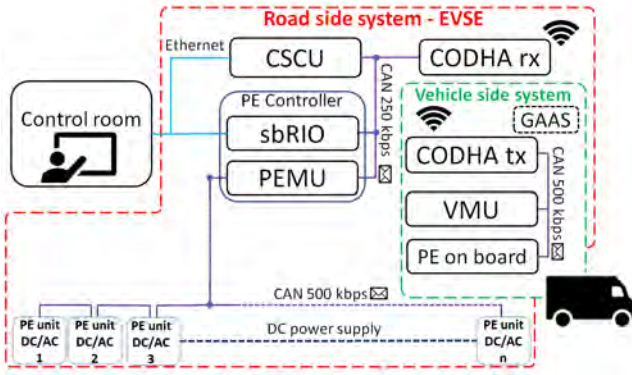Fig. 2: General scheme of the PoliTO CWD power infrastructure.

Fig. 3: High-level block diagram of the Fabric ICT platform, both road side and vehicle systems.

platform able to provide E-mobility services, that may involve also external actors. The road ping side system is developed around the DIPT charging power infrastructure (Fig. 2 for more details). The ICT platform (Fig. 3), which is the focus of this paper, coordinates the activities, on the road side, by means of a CSCU, and manages battery charging, on the vehicle side, by means of a Vehicle Management Unit (VMU). The two sides communicate through COHDA-based [25], [26] Communication and Control Units (CCU). The vehicle system also comprises the Grid Alignment Assistant System (GAAS). Each of the above mentioned components will be detailed in the following.

A. The PoliTO CWD power infrastructure

The DIPT system around which the ICT infrastructure has been developed, is the private mobility-oriented PoliTO Charge While Driving (PoliTO CWD) solution [9]. The system is synthetized in Fig. 2.

The PoliTO CWD prototype consists of a 100 m charging lane with 50 transmitter coils. The system is connected to the low voltage grid by means of an insulation transformer that separates the standard three-phase distribution line from the IPT system. A three-phase active AC/DC converter provides a 650 V stabilized DC distribution line that runs alongside the carriageway powering the DC/AC converters (PE units), each one powering a dedicated transmitter. The transmitter and the related compensation capacitors [27] are directly buried

Fig. 4: Receiver structure mounted under the vehicle. Rear view (a), with the PE in the red box inside the vehicle. Detailed view (b).

under the road pavements at 5 cm from the road surface. The coils are sequentially energized only in presence of the vehicle. Presence detection is carried out by using the power electronics without requiring extra sensors nor road-vehicle communication [9]. Each DC/AC converter is equipped with one voltage transducer and one current transducer both connected at the input (DC side) of the converter. This allows measuring the power provided during the activation of each DC/AC converter independently of what is happening to the other converters along the DC distribution line and avoiding all the critical aspects to the measurements on the AC side [10].

The field generated by the transmitter is linked with the receiver coil placed underneath the vehicle in a dedicated structure, at a 20 cm distance from the ground (Fig. 4). The power received by the receiver coil is rectified by means of a passive diode bridge and then regulated with a DC/DC boost converter that acts also as front end for the vehicle's battery.

B. The EVSE

The ICT-enabled EVSE consists of the CSCU, the PE Controller, the PE units, and the CCU gateway towards the EV (Fig. 3). The CSCU is the component we have designed to co-ordinate the PE control process and the external services. The PE Controller interfaces the CSCU and manages the charging done by the DIPT power infrastructure. It is composed by a single board reconfigurable I/O (sbRIO) device, that controls the charging session at high-level (it will be described in the next sub-section), and a PE Management Unit (PEMU) that manages and monitors the DC/AC PE units of the PoliTO CWD power infrastructure. The CSCU and the PE Controller components realize a distributed multi-master control based on CAN bus [28], [29]. Wireless communication between the EVSE and the EV is performed by two CODHA devices [25], [26].

In order to support integration in an E-mobility landscape, the EVSE must be able to authenticate each EV accessing the charging lane. Moreover, the EVSE has to monitor the amount of delivered energy, and the technical and operational status of each coil along the lane.

In order to guarantee optimal working conditions for the PE units, and to manage the energy exchange itself, EVSE and EV exchange information including:

- Maximum transmittable power by the road-side PE. It may be useful when a reduction in system peak power would be necessary for electric network management necessities.

Fig. 5: CSCU with the CAN interface.

Fig. 6: Authorization State Machine (Auth.-SM).

Fig. 7: Charging Procedure Control State Machine (CPC-SM).

- Resonance frequency of the transmitter and receiver devices. IPT systems operate at a rated frequency which is shared between the road and the vehicle charging devices [13], [16], [17]. Knowing this information allows the system to operate in optimal conditions in terms of transmittable power and efficiency [30]. Furthermore, knowing and modifying this parameter might be mandatory for the power regulation and in view of interoperability between systems operating at slightly different frequency.
- Total energy exchanged at the end of the recharge process. This information is necessary for energy accounting and system efficiency assessment.
- Position of the vehicle. This information is functional for guaranteeing the most effective management and control of the charging lane.

The time-constraint choices we made on communication speed, timed tasks and timeouts in each element of the EVSE depend on the charging infrastructure layout and the vehicle's maximum speed (the delay of the wireless link is hundredfold smaller than the delay tolerance of the system, thus negligible). Particularly, the design choice is to interrupt the charge, after a request, in a time equal to half the time that the vehicle stays above a single coil at the speed of 100 km/h.

C. The Charging Station Control Unit (CSCU)

The CSCU (Fig. 5) is an embedded board hosting a GNU/Linux Debian-based OS. It is equipped with a CAN bus interface to communicate with the local PE controller, a COHDA-based IEEE 802.11p gateway to the vehicle and a network interface (Ethernet, WLAN, 3G) with Internet access to communicate with an EVSE operator in a control room. It provides the following functionalities:

- **AAA-Authentication, Authorization and Accounting**. It is in charge of authenticating an EV, which sends its credentials through 802.11p when approaching the charging lane. The CSCU can check the credentials locally (offline mode) or consult the database of the EVSE-Operator, using the RADIUS protocol [31] (online mode). This inherently foresees the roaming feature, where the Authentication request can be performed by the Home-EVSE-Operator of the given EV. Once Authenticated, the CSCU can decide, offline or online with the EVSE-Operator, whether to Authorize the EV charge or not. If an EV is granted lane access, the power transfer is tracked by the Accounting functionality, which reads the energy meter valu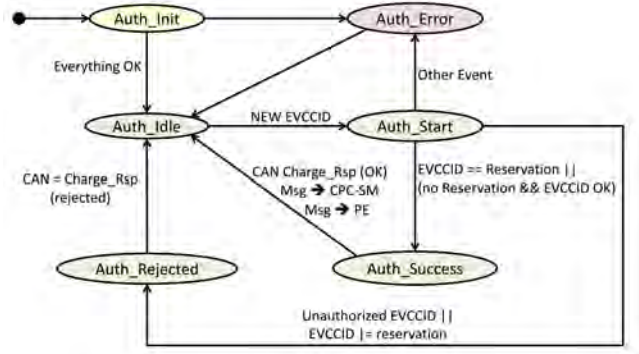es for the current charging session, puts a time-stamp, and sends the data to the EVSE-Operator over an encrypted channel, ensuring integrity and confidentiality. This is the basic information that is needed by a billing service operator, e.g., an E-mobility actor such as E-mobility platform, EVSE-Operator, etc.
- **Booking**. In Fabric, the EVSE Operator supports reservation of a charging facility using the ETSI TS 101 556-3 standard. In collaboration with the AAA block, the Booking functional component assists the EVSE Operator in the pre-reservation, reservation, cancellation, and update procedures.
- **Arrival monitor**. This module exploits an Automatic Number Plate Recognition (ANPR) camera, connected via Ethernet and placed in the actual proximity of the coils, to check if the EV now entering the charging lane was authenticated. Authentication was done by the AAA module when the vehicle was farther from the transmitter coils. This second, optical check is needed to control the physical access to the lane.
- **State monitor**. It monitors the state of the EVSE (CSCU and PE Controller), by tracking the state of each component through the CAN messages, and reports it to the backend or any relevant E-Mobility ICT service (e.g., to the EVSE operator for maintenance and to the navigation operator for notifying the drivers of a fault).

D. CSCU logic

The CSCU logic is designed to combine and coordinate the DIPT process and the EVSE ICT-services. This requires two phases, for each charging session. The first one manages an EV access, from the first communication contact until the ANPR detects the plate number. Then the PE Controller takes the control of the actual charging session. Thus, the CSCU involves two state machines: the Authorization State Machine (Auth.-SM, Fig. 6) and, the Charging Procedure Control State Machine (CPC-SM, Fig. 7).

We designed two state machines to be able to serve many EVs at the same time, by using the Auth.-SM to reply to EV authorization requests as fast as possible, and then assigning a CPC-SM to each EV as soon as it has been authorized. The CSCU sends over the CAN bus the state of each one of its SMs. In this way, for instance, reservation information from the Internet service implementing the ETSI TS 101 556-3 standard can reach the PE Controller. In case the EVSE is reserved for a different EV than the currently requesting one, the Auth.-SM rejects the request, and waits for the right EV. Once an EV is authorized, a CPC-SM is created. The CPC-SM waits (CPC Waiting state) for an Event from the Arrival Monitor, which checks the plate of the vehicles passing by the coils. Once the plate is successfully detected, the CPC-SM notifies it to the PE Controller and switches to the CPC Arrived state. From now on, the PE has the control over the CSCU (i.e., the CSCU follows the state of the PE Controller). As soon as the power transfer starts, the CPC-SM changes into the CPC Charging state. The CPC-SM waits in this state until the PE Controller completes the charging. Then, the CPC-SM switches to the CPC End state and asks the PE for the metering values, so to be able to account the charging session, create a Charge Detail Record, and send it to the relevant ICT-actor (e.g. E-mobility platform, EVSE-operator, etc.). In case of any error (either on the road or vehicle side) the CPC-SM goes into the CPC Error state, and ends the accounting.

Thus, on one hand the CSCU controls the PE based on EV authentication and authorization, on the other hand it feeds ICT services with detailed information from the PE about the DIPT process for each EV.

E. Power Electronic Controller

At lower level, the road side is managed by the PE Controller, which is constituted by an sbRIO-9606, by National Instruments (Fig. 8) and a PE Management Unit (PEMU). The sbRIO is a re-configurable device successfully adopted in several engineering applications (e.g. [32]–[34]). We chose it because of its high flexibility, given by a 400 MHz industrial processor and a Xilinx Spartan-6 LX45 FPGA, and the availability of several interfaces, such as Digital Input Output channels, CAN, serial RS232, USB and a built-in Ethernet. The sbRIO processes information from the CSCU via CAN messages and, through the PEMU, drives the PE units and monitors their operative status, also getting information about the transferred amount of energy, that is finally transmitted to the CSCU. The connection with the Control room is due to monitoring.

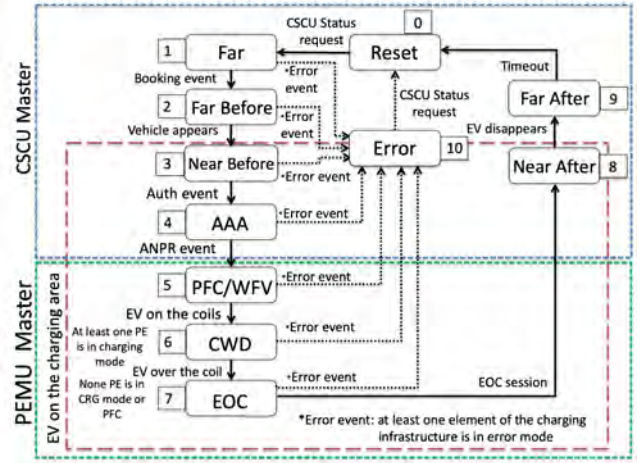Fig. 8: Aspect and connections of the sbRIO board.

Fig. 9: sbRIO SM. The blue box contains the states in which the CSCU is the master. The green box contains the states in which the PEMU is the master. The states reached when the vehicle is in the charging area are in the red box.

F. sbRIO control logic

The sbRIO real time SM follows a space time line that depends on the vehicle position in the charging area and evolves on the basis of messages from the CSCU (booking, authorization), from the EV (vehicle position) and the PEMU. As the sbRIO is the connecting element between the high and low level control, its SM, in each step, represents the synthesis of the operating state of the whole EVSE. The sbRIO SM logic is built in a deterministic timed loop, allowing the realization of the real time control strategies of the charging process. The control logic, sketched in Fig. 9, involves the following states:

- **Far**. In this condition, the sbRIO and the CSCU establish a communication every second to verify the working state of the communication link. The PE units are in the off-state but, once per hour, they are switched on for auto-monitoring tests verifying power components, control and communications. At the end of the tests, the system remains in the Far state, or goes in the Error state. When an EV requests a recharge booking, the CSCU sends the message in the ground CAN network. This message causes the switch to the Far Before state.
- **Far Before**. In this state the sbRIO triggers the auto-monitoring test of the PE units. The detection of a fault

causes the switch to the Error state of all the CAN network nodes. The sbRIO waits up to 2 minutes for messages via COHDA from an approaching EV. If a message arrives, the state becomes Near Before, otherwise the system goes in the Error state.

- **Near Before**. The sbRIO waits for a message from the CSCU that has to validate the authorization of the approaching vehicle, which sent its electronic ID through COHDA (802.11p). If authorization is granted, the state becomes AAA. If the approaching vehicle is not authorized, the state becomes Near After. If no messages arrive from the CSCU or the communication with vehicle is lost for more than 2 minutes, the sbRIO State Machine switches to the Error state.
- **AAA-Authentication, Authorization and Accounting**. In this state, the sbRIO waits up to 1 minute for a CSCU message stating that the ANPR camera has detected the physical ID of the EV (i.e. the plate number) and verified that it corresponds to the booking ID previously received through COHDA. This second check (made in proximity of the transmitter coils) prevents that an unauthorized vehicle, overtaking an authorized one, enters the charging lane without authorization. If a positive message arrives, the state becomes WFV-Waiting For Vehicle. If no message arrives within 1 minute, the state machine goes in Error state.
- **WFV-Waiting For Vehicle**. In this state the sbRIO commands to the PEMU to start the charging procedure. Then, the first PE (i.e. the DC/AC that supplies the first coil of the charging lane) starts the identification procedure, so to transfer power only when the vehicle is right over its coil. The PE starts injecting a small current of 2 A in the transmitter coil while measuring the voltage applied to the coil itself. When the vehicle is above the transmitter, the presence of the receiver causes a variation in the transmitter current and voltage, and this variation is used to detect the presence of the vehicle (Fig. 10). Once the presence of the vehicle is detected, the PE starts supplying the coil at full power. Simultaneously, the PE changes its state to Charging and notifies the CAN network causing the subsequent PE on the charging lane to start the identification procedure. This activation procedure allows supplying only one coil at a time. Moreover, the identification procedure is maintained for a limited time interval of 5 seconds. If the identification does not occur within this interval, the PE goes in Error state and it is turned off. This allows to keep losses low as the current used for the identification is not supplied indefinitely. At the same time, this guarantees that there is magnetic field only in a small section of the charging lane close to the vehicle so to avoid the possibility of human exposure.

The PE units can assume four different sub-states in parallel to the sbRIO's WFV-Waiting For Vehicle and CWD-Charge While Driving (described later) states:

- **PFC-Prepare For Charging**. The PE executes the vehicle detection.
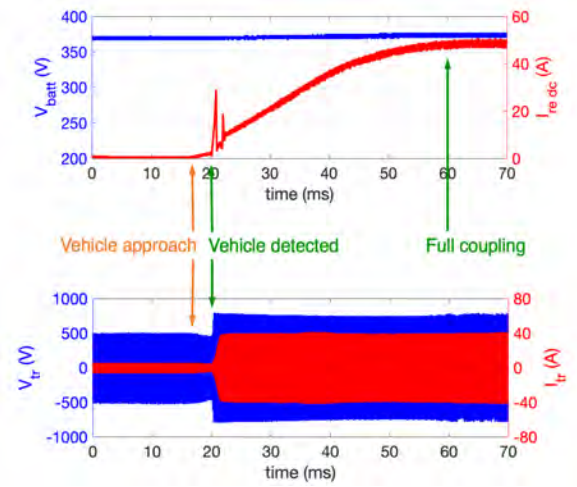

Fig. 10: Vehicle presence identification through the on-ground PE. The upper graph shows the waveforms of the battery voltage (in blue) and the rectified current of the receiver (in red). The lower graph shows the waveforms of the voltage at the output of the PE converter that supplies the transmitter coil (in blue) and the current flowing in the transmitter coil (in red).

- **Charging**. The PE supplies its transmitter coil.
- **EOC-End Of Charge**. The vehicle has left the transmitting coil.
- **Fault**. State reached if the PE control detects an anomalous behavior of the PE. The PEMU and then the sbRIO consequently switch to the Error state.

In WFV-Waiting For Vehicle state, the states of all the actors involved in the charging process are directly dependent on the state of the PE. The PE is monitored by the sbRIO that consequently adjusts its own state and notifies the other components through the network. The detection of the presence of the vehicle on the first coil causes a change in the PE and in the PEMU states, which leads the sbRIO into the CWD-Charge While Driving state. In cascade, all the elements of EVSE move to CWD-Charge While Driving. (An example of the evolution of the state machines is visible in Fig. 17 in the Results and discussion section).

- **CWD-Charge While Driving**. This state is entered when the PEMU goes in the Charging state. This means that at least one PE unit is in charging mode. When a PE unit enters the charging mode, it sends a message on the PE dedicated CAN. The next PE unit is then triggered, in order to start its own vehicle presence identification process. In cascade, every single PE unit will then try to identify the presence of the vehicle. The sbRIO remains in the **CWD-Charge While Driving** state until a notification of EOC-End Of Charge arrives from the PEMU, or a request of interruption comes from the vehicle. The PEMU communicates the EOC-End Of Charge if no PE units are in Charging or PFC-Prepare For Charging mode. Entrance, exit and all the actions in the CWD-Charge While Driving state are controlled by the PEMU. It is worth noting that an interruption request from the vehicle can be managed through the CAN-wireless communication network.

- **EOC-End Of Charge**. Once reached this state, the sbRIO processes the information about the charge, evaluates power and energy consumption, and communicates the results to the CSCU, when requested. When the response is sent (or after up to 2 minutes), the state becomes Near After.
- **Near After**. In this state, the sbRIO checks the presence of the EV, by verifying the presence of COHDA messages. If 5 seconds elapse without receiving messages, the SM goes in the Far After state. In this state, the sbRIO also requests a last (post-hoc) check of the functioning of the PE units.
- **Far After**. The SM commands the turn off of the PE units.
- **Error**. During the entire execution of the SM, the sbRIO system goes in the error state if:
  - an error message arrives from the CAN bus;
  - a value measured by the measurement board of the PE units is out of the admissible range;
  - a timeout flag points out an anomalous behavior of the vehicle (e.g., the vehicle is in CWD-Charge While Driving but is not communicating, the vehicle remains in charge for too long, there is no info from the PE on board).

Generally, a robust EV-EVSE communication is essential for charging solutions [37], especially during power transfer. With the different time-out parameters, the communication fault tolerance of the system can be adjusted. E.g. for the authentication and authorization state, the system can be tuned to have a time-out of up to 5 seconds. For the CWD-Charge While Driving state, a time-out higher then 500 ms, cannot be tolerated.

The periodic communication with the CSCU has a reset function on the sbRIO SM. The Error state, in fact, leads the PE units in a protection condition (electronic switches turned off/opened) to guarantee the safety of the devices. This state can be reached at any time, in case of an error message, whichever the sending element is. This prevents danger conditions caused by components malfunctioning or EV driver's misbehavior. If the error is solved, the reset function allows the sbRIO, and then the overall system, to start a new charging process.

G. The Grid Alignment Assistant System (GAAS)

A key module for effective and efficient DIPT is the optical Grid Alignment Assistance System (GAAS), that computes in real-time the misalignment between the axis of the vehicle and that of the charging grid (i.e., the coils) in the road (Fig. 11, described in the following). The goal is to keep the vehicle always within a ± 20 cm range from the center of the grid [35], using low-cost and low-power consumption hardware and software components, in order to work in conditions as close as possible to those in production. As optical sensor, we used the Logitech c920a high definition (1920×1080) webcam to capture 30 frames per second of the road ahead. The webcam performs automatic luminosity adaptation. Mounted on the top-middle of the windshield, using a suction cup, the camera
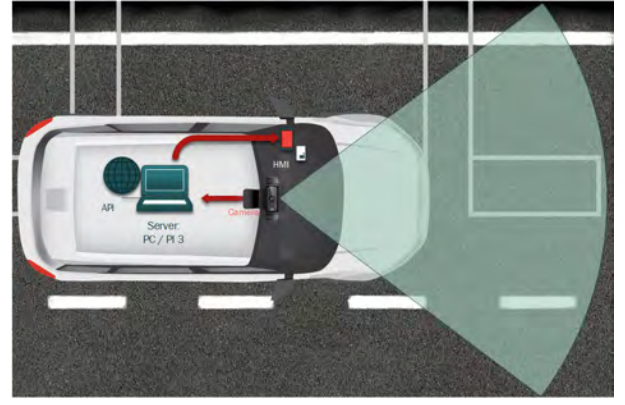

Fig. 11: GAAS deployment schema.

Fig. 12: GAAS's linear gauge in the OBU tablet.

is connected to a server-node Raspberry Pi 3 running Python 3.7.0 on Linux OS. The Python server node processes each frame, estimating the current position of the centre of the vehicle w.r.t the centre of the grid. The computed alignment offset (in cm) is displayed to the driver as a pointer across a gauge scale as part of the Human-Machine Interaction module implemented in the on-board unit (OBU) on a tablet (Fig. 12).

A major assumption of the algorithm is that the car is in the charging lane, which allows spatially masking the image, better focusing the recognition. It is also assumed that the system knows the size of the grid and of the lane, which is needed in order to notify the driver of the precise offset from the center of the grid in cm. The (constant) offset of the grid from the centre of the lane may also be known, to allow grid-keeping be based on lane detection only. The system, in fact, is designed to recognize both the grid and the lane. In case of grid recognition failure (e.g., for sun glare, colour blending between the grid and the surrounding pavement), the center of the grid is estimated through lane recognition. Thus, we implemented two parallel image processing pipelines for each frame: one for grid recognition and one for lane recognition. Three main steps formulate each frame's processing: line detection, borderlines recognition (clustering and averaging the detected lines), and grid mid point estimation. Lanes were considered of different colors, and also the grids were of two different types, for material and color, in two different areas of the track (Fig. 13). Lane recognition uses also an online algorithm to estimate a lane position based on history when not directly recognized (e.g., sometimes during gaps in dashed
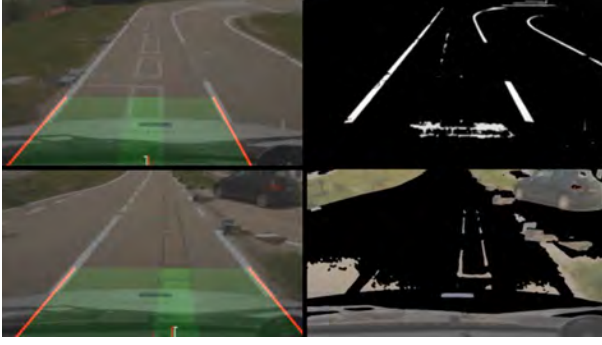
Fig. 13: Color recognition (left) and gaussian/median filters (right).

lines). More development details are provided in [36].

IV. TEST SITE IMPLEMENTATION AND RESULTS

A. Test site

The Fabric platform has been implemented and tested inside the MotorOasi Piemonte safe driving track. This track, managed by TecnoSitaf s.p.a., is located in Susa, Italy. The map of the test site is shown in Fig. 14. The figure shows all the functional areas related to the states of the sbRIO control logic. The building indicated with the yellow dot hosts the Control room and the Power room. All the data coming from the charging process are stored inside this building. The Control room hosts the computers that monitors the ICT platform by means of a LAN connection. In the Power room, the connection with the electric distribution network takes place and here the insulation transformer and the AC/DC converter are placed, that power the DC distribution line to supply the charging lane (please refer to Fig. 2). From the Power room, all the other AC low voltage branches start, that power the Fabric platform ICT components. The 650 V DC distribution and the auxiliary 230 V AC distribution are provided by underground cables that go from the Power room to the road cabinet. The cabinet, indicated by the red dot, hosts the CSCU, the PE Controller, and the communication interfaces to the vehicle (COHDA), to the PE on ground (CAN 500 kbps), and to the Control room (Ethernet) (Fig. 15). The two distribution lines are split in two branches from the road cabinet to all the DC/AC converters on ground. A view of the PoliTO CWD charging lane is depicted in Fig. 16.

B. Results and discussion

Several tests have been performed to verify effectiveness and robustness of the infrastructure. The tests have been performed for one year (for a total driving time of about 120 hours), in daylight hours, under different weather conditions (from snowy and cold days in winter, with a temperature of about -10 °C to hot summer days, with temperatures of about 40 °C), different vehicle speeds, different levels of power requested by the vehicle charging equipment, different maximum power limitations imposed by the on-ground PE converters. The functionalities of the Fabric platform have proven not to be influenced by these different operating conditions.

Fig. 14: Functional map of the Fabric test site.
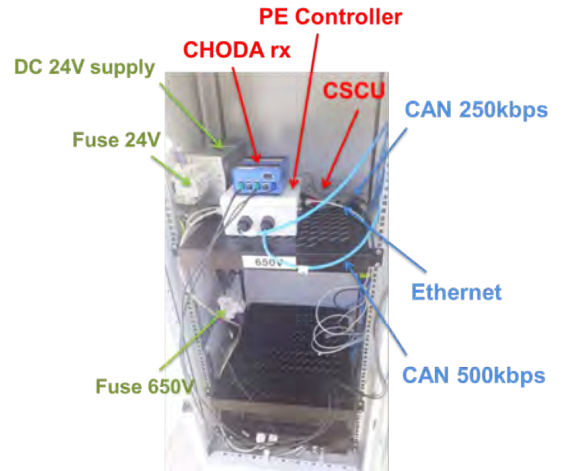

Fig. 15: Road cabinet containing CSCU, PE Controller, and their communication interfaces.

Fig. 16: The EV in the charging lane.

An initial set of tests was performed with one equipped EV and other cars running on the test site in order to verify the correct sequence of booking, plate recognition and permission to charge, and to tune up the timing of the element of the ICT platform.

The second more substantial set of tests has been conducted with the equipped vehicle to verify the effectiveness of the overall platform in managing the charging process.

An example of the EVSE operation for a 40 km/h speed test, is reported in Fig. 17. The figure represents the states of each EVSE element during a charging session. The different events that lead to state variations are shown. The related waveforms acquired on board the vehicle are reported in Fig. 18.

Fig. 17 illustrates the sbRIO operations during the passage of an authorized vehicle. Once the vehicle's approach to the lane is confirmed by the Arrival monitor, the sbRIO drives the PEMU in the PFC-Prepare For Charging status. Then the sbRIO switches from a master behavior to a slave behavior. Once verified the presence of the vehicle above the coil, all the single PE units automatically switch from PFC-Prepare For Charging to Charging status. Consequently, the sbRIO switches from WFV-Waiting For Vehicle to CWD-Charge While Driving. In correspondence of a damaged coil (about in the middle of the lane - see next paragraph), the related PE remains in PFC mode without activating the identification procedure. If at least one PE unit is in Charging mode, the PEMU is in charging mode. If no PE is in Charging nor in PFC-Prepare For Charging mode, the PEMU goes to EOC-End Of Charge. Information related to the charging session is then sent to the CSCU, that forwards it to the EV, to the Fabric backend, and any relevant E-Mobility ICT service.

In both Fig. 17 and Fig. 18 a faulty coil is visible, whose effect is the presence of a "hole" in the sequence of pulses that clearly indicate the passage of the vehicle above the transmitter coils. The coil fault was caused by a failure of the compensation capacitor embedded with the coil. We then exploited the presence of this coil to test robustness of the high-level control. After the faulty coil, a reduction in transmitted power appears, due to the misalignment of the vehicle. The power supply reaches a minimum in correspondence of a lateral misalignment of about 15 cm, then the driver compensates the misalignment thanks to the indications by the GAAS. A second strong decrease occurs at the end of the charging lane where a curve (Fig. 14) forces the driver to steer, causing a new stronger misalignment.

Concerning the GAAS, the tests have shown that the most critical parameter for performance is the kernel size of the low pass filters (Gaussian or Median) that are used for noise reduction at the beginning of the two image processing pipelines described in III.G. The kernel is convoluted over all the pixels of each input frame, in order to reduce noise. With a 5×5 kernel size, we achieved a rate of 24 frames per second (fps), on the Raspberry Pi 3 platform. The rate is acceptable for human perception, while accuracy lies within ± 10 cm 80% of the time, and 100% within ± 20 cm. This allows communicating to the driver most of the time if the vehicle is currently within the suited energy transfer
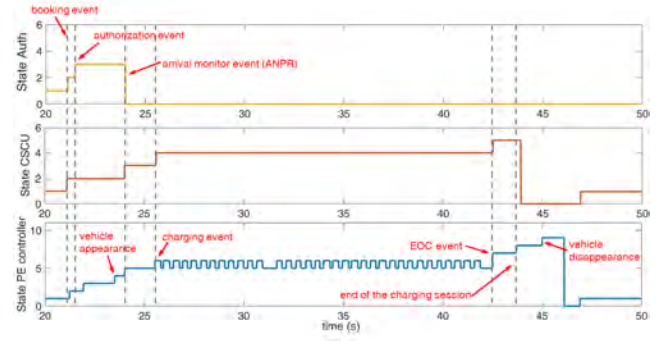

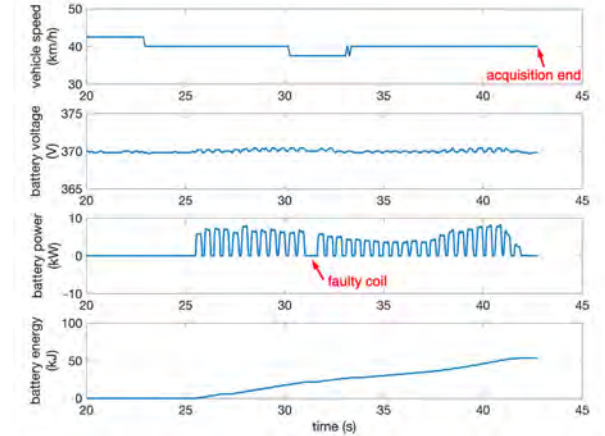Fig. 17: Multi-master behavior during a vehicle charge test.

Fig. 18: Waveforms of the main quantities acquired on vehicle board from the CAN bus. Battery voltage, power and cumulative received energy in the battery derived from the data provided by the battery BMS.

efficiency range (considered equal to ± 20 cm) [35]. Vision errors were typically due to factors such as glare in the asphalt, color blending and small differences in the size of the lines/gaps. With smaller kernel sizes, accuracy dramatically drops, while with larger kernels the system crashes because of CPU overload. Utilization of dedicated computing units, such as a GPU, should allow completely fulfilling the accuracy requirement. The vision system was tested in different weather conditions. With snow on the roadside, the glare in intensified, but the camera's self-tuning functions as well as an anti-glare shield. In case of rain, since the camera is placed behind, we noticed a significant drop in detection accuracy when the windshield is left un-wiped for a certain duration depending on the rain intensity. Night mode was not tested. however, a similar scenario occurred on a late evening test of a cloudy day. under that circumstance, the system's performance was intact since the vehicle's headlight shone particularly on the area of interest for the grid detection. We must note that high beams from oncoming vehicles would blind the camera for a couple of seconds until its auto-tuning software adjusts the brightness.

Compared to other grid coupling approaches (e.g., [23], [24]), GAAS looks exposed to more challenges in terms of failure causes for camera misplacement and weather or windshield conditions. However, it is more immune to elec-

tromagnetic interference. Our system is much cheaper than alternatives that require road equipment. Moreover, most of GAAS' hardware and software components are upgradable in a singular fashion, without affecting other components.

The ANPR camera is a critical component, requiring an accurate positioning and calibration. We had several failures in vehicle recognition due to lighting conditions and readability of the vehicle plate. Conversely, no unequipped vehicle was wrongly authorized to recharge.

Overall, the tests allowed several improvements on aspects related to the power infrastructure such as the displacement of the coils and their integration in the road infrastructure, and the optimal control of the PEs on ground and on board vehicle.

On the ICT side, the tests provided feedback on the effectiveness of the implemented platform. Particularly, they showed that the platform successfully allowed to:

- establish a safe communication with the vehicle;
- provide a stable and repeatable booking and authorization sequence enabling the charge of the authorized vehicle only;
- activate the automatic identification procedure only when the vehicle is close to the charging lane, with significant power savings;
- correctly manage the entire charging process guaranteeing a correct sequential powering of the transmitter coils with sensorless vehicle presence detection;
- enable real time communication among all components;
- permanently monitor the charging process;
- make information on each charging section remotely available for billing and data analysis;
- assist the driver in keeping the vehicle aligned to the grid so to maximize the energy exchange.

C. Limitations

The Fabric system was designed to manage the presence and the charge of more than one vehicle simultaneously. However, we could not field-test this important feature, as the project made only a single EV available.

In our implementation, each fault event simply leads each node of the CAN network in the error condition and determines the stop of the charging. The creation of an error handling procedure in the SM would allow more smooth operations.

The charging infrastructure communications have been based on a CAN bus, given its great usability. However, this protocol is not easily scalable, and an increase in size of the charging infrastructure, with a related increase in the number of charging zones and of vehicles, calls for adopting a different communication standard, that should be faster, more stable and better suited to cover longer distances.

The system has been stressed at speeds around $40 \mathrm{~km/h}$, which is typical for urban scenarios. In few cases, a high speed of $70 \mathrm{~km/h}$ was reached, without any issues. Finally, the bandwidth of the PE control, the frequency of the involved magnetic field, and the bandwidth and the timing of the communications were abundantly high compared to the dynamic of the vehicle, which makes us argue that the system can effectively work also for highway speeds.

V. CONCLUSIONS

The paper has presented a new E-mobility enabling platform featuring a high level CSCU (it makes the PE control process aware of the external services and communicates to the cloud information on each charging session) and a PE Controller (a middleware that controls the charging process keeping into account also external world information). To the best of our knowledge, this is the first paper presenting and assessing in road tests an ICT platform for managing DIPT road lanes.

Tests have been performed in a safe drive track, in Italy, to verify effectiveness and robustness of the infrastructure, for one year, under various weather conditions, for a total of 120 drive hours. Tests have shown suitability of the implemented platform in terms of ability to authenticate and authorize a vehicle also through a remote service, sequentially control each coil so to emit power only during the passage of the vehicle (detected sensor-less), monitor the charging process, delivering of charge information to the cloud (e.g., for billing), assist the driver in keeping the vehicle aligned to the grid so to maximize the energy exchange. We argue that this set of features constitute a significant innovation in view of future scenarios with a widespread adoption of DIPT.

Despite the developed system is intended to manage the simultaneous charging of multiple vehicles, we could not test this scenario in the project, which is left for future work. It will also be interesting to study the integration of the GAAS vision system with the ground infrastructure, so to further optimize the energy exchange.

The experience and results gained in this work contributed to the improvement of the standard ISO - 15118 on EVSE-EV communication for conductive charging [37] where the work done in [38] is now included in the draft of the follow up version of the protocol. Overall, we hope that the experience and results presented in this work can contribute to shape the future of the DIPT Technology and of e-Mobility services.

ACKNOWLEDGMENT

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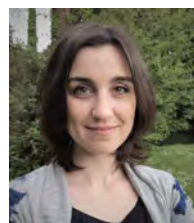
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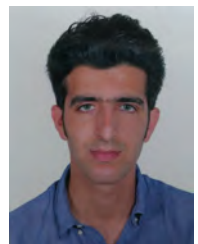
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