Cooperative approaches for dynamic wireless charging of Electric Vehicles in a smart city

Leandros A. Maglaras #1, Frangiskos V. Topalis *2, Athanasios L. Maglaras **3
# Department of Computer & Communication Engineering, University of Thessaly, Volos, Greece
* Electrical and Computer Engineering Department, N.T.U.A., Athens, Greece
** Electrical Engineering Department, T.E.I. of Larissa, 41110 Larissa, Greece

Abstract—In this paper, a method of electric vehicles charging with the use of large truck/bus vehicles moving along national highways and provincial roads is proposed and described. The method relies on charging vehicles from trucks while moving either with plug in electric connection or by electromagnetic induction via loosely coupled coils. Open research challenges and several avenues or opportunities for future research on Electric Vehicles Charging are outlined. The proposed method overcomes the disadvantages of the so far known techniques. The advantages of this method compared to the so far proposed methods are a) economical, easy and safe procedure, b) increase of the energy transfer efficiency factor, c) minimization of the delay in vehicle movement during the charging procedure and d) reduction of the environmental contamination with CO2 or electromagnetic radiation.

Index Terms—Vehicular communications, Electric Vehicles, Inductive Power Transfer, LTE.

I. INTRODUCTION - MOTIVATION

In the future transport area, electric vehicles (EV) are considered as replacement of internal combustion engine driven vehicles, especially for the CO2 reduction and alternative energy perspective. Electric cars have the potential to reduce carbon emissions, local air pollution and reliance on imported oil [1]. In Europe, the European commission aims to reduce road transport emissions by 70% by 2050 [2]. Taking to account that the road transport is expected to double by 2050, passenger cars need to significantly reduce their emissions. Advanced Internal combustion engine (ICE) technologies are expected to enable emissions reduction but it is rather impossible to meet long term emission targets.

Inter-vehicle communications (IVC) [3] on the other hand can be used in order to reduce traffic jams, having a direct impact on CO2 emissions. Routing vehicles to more environmental friendly paths is already used in order to reduce overall mileage and CO2 emissions. Innovative eco-routing methods based on vehicle to vehicle (V2V) communications are beginning to gain attention [4]. Other methods that are based on TMCs (Traffic Message Channels), smart phone applications and GPSs try to cope with the same problem. The combination of LTE and DSRC communication capabilities of vehicles and their drivers can enhance the performance of these methods. Road users others than cars, e.g. pedestrians, cyclists etc can play an active role in data dissemination with the use of LTE.

Electric vehicles and especially plug-in electric vehicles (PEVs) are penetrating the market since they are currently counted as zero emissions vehicles. Except from additional cost of their lithium-ion battery pack that makes the car more expensive than conventional vehicles, there are also some other factors that discourage drivers from switching to an EV. Battery electric vehicles (EV) have a limited driving distance [5]. This limited driving range must be added to the current lack of charging infrastructure as well as the total time needed to recharge such a vehicle.

In this paper we present current methods and architectures that aim to increase electrical vehicles range through wireless charging, optimal placement of charging stations or eco-routing. Based on the disadvantages of these methods we propose new cooperative approaches that exploits IVC, LTE and IPT for smart wireless charging of vehicles by mobile stations. We finally discuss about research challenges and future trends.

II. INCREASING A CARS ALL-ELECTRIC RANGE

A. Charging of Evs : Categories

Wired charging.

Electric vehicles are plugged for charging on the existing electrical grid infrastructure, but some times the electrical infrastructure is inadequate to support this additional energy demand since it is not able to support the high power fast charging stations. The presence of several contemporary charging requests could cause overload conditions in local nodes of the grid if the charging processes of the PEVs are not properly managed and scheduled.

One alternative to the fast charging stations [6] is to have MCS that would have high storage capacity. A mobile charging system (MCS) for Electric vehicles (Ev) is presented in [7]. These stations can be a solution when electrical infrastructure of the local grid would not be able to support high power fast charging stations.

Smart scheduling strategies can be profitably used to manage the PEV charging problem [8]. Smart energy control strategies based on quadratic programming for charging
PHEVs, decrease the peak load and flatten the overall load profile. The usage of Information and Communication Technology (ICT) in a Smart Grid environment is a proposed solution [9], [10]. Authors in [11] state that the deployment of smart Grid communication architectures by using small embedded systems in a hierarchical way or manner fashion can enable the distribution grid to charge a large number of EVs without the need to carry a high workload.

**Dynamic Wireless charging**

Dynamic wireless charging is gaining more ground, since it enables power exchange between the vehicle and the grid while the vehicle is moving. Installed infrastructure can be utilized very effectively, since many vehicles use the same road segments that are facilitated with dynamic charging capabilities. Dynamic charging can take place in a parking lot, in a bus stop during passenger disembarkation, along a highway or near traffic lights.

Recently Telewatt project introduced an original approach consisting in reusing existing public lighting infrastructures for dynamic charging. A fraction of the power not consumed by the lamps at night can be used for the benefit of the charging stations. The service is accessible by a smartphone application, where clients specify to the TeleWatt server their destination and their battery level and take as a response a list of available charging terminals close to the destination [12].

Hevo announced a novel dynamic charging system where manhole covers will be used as charging stations. Hevo Powers pilot program is scheduled to be performed in New York City in 2014.

Two On-Line Electric Vehicle (OLEV) buses that can charge during travel have been put into service for the first time in the world on normal roads in the city of Gumi - Korea by the Korea Advanced Institute of Science and Technology (KAIST) [13]. The power is transmitted through magnetic fields embedded in the roads. Power comes from the electrical cables buried under the surface of the road, creating these magnetic fields. The length of power strips installed under the road is generally 5%-15% of the entire road.

In [14] authors present a method for Power Transfer between Electric Vehicles, where drivers “share” charge with each other using Inductive Power Transfer (IPT) of charge between vehicles at rendezvous points. One major issue in this concept is the technology requirements that have to be met by passenger vehicles in order for this solution to be feasible.

Dynamic charging of vehicles raise health issues related to the leaking magnetic flux from Inductive Power Transfer (IPT).

**B. The charging station location problem**

Thoughtful siting of public charging stations can ease consumer range anxiety while offering a lower cost approach to integrating EVs into the transportation market. Authors in [16] propose a method to anticipate parking demands and more efficiently locate EV charging infrastructure in new settings and/or subject to different constraints.

Authors in [17] used Lisbon, Portugal as a case study where they determined not just the locations, but also the capacity of stations to be installed at each location trying to optimize the demand covered within an acceptable level of service. In [18] authors try to built a comprehensive objective function considering geographic information, construction cost and running cost in order to achieve optimal planning of charging stations.

Authors in [19] describe an electric vehicle battery swapping station. They present a business case scenario where customers have access to battery swapping stations, where they can meet their motion energy requirements by swapping batteries for charged ones, in a short time.

**C. Eco-routing of EVs**

Similar to eco-routing for conventional vehicles, novel methods are being developed and used in order to reduce the energy consumption of EVs [20], [21]. Authors in [20] have developed an eco-routing navigation system which determines the most eco-friendly route between a trip origin and a destination. With the use of a Dynamic Roadway Network database that integrates historical and real time data they manage to reduce CO2 emissions. Based on their previous work they now aim to create an eco-routing algorithm that will be incorporated into a prototype eco-routing navigation system for electric vehicles. In [21] authors moved a step further by creating a routing system that could extend the driving range of EVs through calculating the minimum energy route to a destination.

**III. Mobile energy disseminators**

The above mentioned solutions proposed in bibliography have the following disadvantages a) inability for vehicles to cover long distances and important (or significant) delay regarding vehicle movement due to course change and stop for recharge, b) the pollution of environment with electromagnetic radiation and c) the small efficiency factor of the charge transfer carried out by conduction from a distance.

In this section cooperative mechanisms for dynamic wireless charging of EVs that are based both on Wireless communications and inductive energy transfer between vehicles are proposed. Novel communication means, integrating vehicular communications with smartphones (V2X for short) can be combined with smart grid capabilities and wireless energy transfer technology concluding towards the building of a Smart City.

**A. System overview**

In the proposed methods the charging of vehicles with the use of trucks/busses can be achieved while in motion or immobilized. The procedure will provide vehicle charging by an electric plug in connection (or process), or by electromagnetic induction with the use of Tesla coils. Immobilized charging can take place in predetermined road points (for example parking areas) in order to avoid traffic obstruction and in this case the method of the plug in electric connection is
preferable. Busses can act as energy disseminators in an urban environment while trucks may have the role of energy chargers mostly in highways.

The proposed charging system of vehicles from other truck vehicles in motion, displays similarities with the charging system of military aircraft from other cargo aircraft in flight. The vehicle requiring electric charge will approach the appropriate truck, after a preceded agreement, from the rear or the front end depending on the vehicle construction.

A synchronization of the vehicles movement will be executed via wireless communication mainly controlled by the truck/bus. From the analysis made it is apparent that it is preferable for reasons of safety and better management of the system the vehicle needing charge to move ahead of the truck. There will be a special joint magnetic arrangement concerning the vehicles, as well as a special interlocking arrangement in order for the two vehicles to approach and keep in contact, even while in motion, and for as long as the charge transfer takes place.

Charge transfer can be achieved with electric plug in connection, or by electromagnetic induction. During the electromagnetic induction transfer the charge and consequently the power transfer will be accomplished with the use of two detached subsystems of magnetic coupling of high efficiency. The electromagnetic subsystems will include magnetic coils, which will cooperate and function like the primary and the secondary coils of a transformer. The two coils will have loose coupling using air as the proper medium. This way of coupling (like Tesla coils) has proven to be more efficient than the ferromagnetic materials. The primary coil of the truck may be movable and able to insert in the bigger diameter coil of the vehicle, in order to improve the efficiency factor of the power transfer process and minimize the leaking magnetic flux. The two subsystems will be specially shielded (faraday cage) in order to protect occupants and bystander vehicles or pedestrians from electromagnetic radiation.

The truck/bus will carry high capacity batteries, and if needed the whole relative electric system to convert voltage from DC to AC voltage of high frequency. It will also need to carry a conventional internal combustion engine, as well as a proper electric generator, used to produce electric energy in an emergency situation. The advantages of the proposed system are a) high efficiency factor (especially when the charge transfer is achieved via electrical plug in connection) b) very short delay regarding the moving of the vehicles c) significant reduction of environmental pollution and d) coverage of special needs in exceptional climatic conditions or failure conditions.

B. Cooperative mechanisms

Energy exchange can be facilitated by Inductive Power Transfer (IPT) between vehicles and/or by installing a roadside infrastructure unit for wireless charging. However, given the vast expanse of road networks, it is impractical to have infrastructure units on every road segment due to prohibitive costs. IPT allows efficient and real-time energy exchange where vehicles can play an active role in the energy exchange procedure.

On the other hand, the use of mobile nodes as relay nodes is commonly used in VANETs. In a VANET mobile relay nodes can serve as carriers and disseminators of useful information. Influential spreaders, nodes that can disseminate the information to a large part of the network effectively is an open issue in ad hoc networks. Nodes with predefined or repeating routes that can cover a wide range of a city region can do the work of Road Site Units while exploiting their mobility in order to provide higher Quality-of-Service (QoS).

Similar to information dissemination, special nodes, like busses(trucks), can act as energy sources to EVs that need charge, in order to increase travel time. Those vehicles, now on called mobile energy disseminators (MED), use electric plug in connection or Inductive Power Transfer (IPT) in order to refill starving EVs. Busses can play the role of MED since they follow predefined scheduled routes while their paths cover a major part of a city. Busses can be fully charged when parked, before beginning their scheduled trip, and can be continuously charged along their trip by IPT stations installed at bus stops. Additional technology requirements that these vehicles may have in order to operate as energy sources, is an open issue, but it is rather more feasible in the near future, to have these features installed to large public vehicles than to passenger vehicles due to additional cost and space requirements.

In the following sections we present two cooperative mechanisms, one based on Dedicated short range communication (DSRC) capabilities of vehicles and the other on Long Term Evolution (LTE) technology. A network $G = (N, L)$, where $N$ is the set of nodes (intersections) and $L$ is the set of links (road segments), is considered. $V$ is the set of electric vehicles that move in the network and $M$ is the subset $(M \subset V)$ of electric vehicles that can act as mobile charging stations (MED).

C. IVC system description

In order to state its presence, $MED$ i periodically broadcasts cooperative awareness messages (CAM). Each beacon message consists of node Identifier (Vid), node location, scheduled trip (Sld a subset of set $L$), current charging capability (CC) and energy value (€ / KWh). CC is the current energy that the mobile charging station can dispose for charging of vehicles according to its energy needs. These messages are disseminated by all vehicles that act as relay nodes.

EV $j$ that needs energy, upon receiving a CAM by an $MED$ i performs the following steps:

1) Checks whether $MED$ is on his route or not according to their current positions and destinations
2) Checks whether the CC level is high enough in order to cover its energy needs
3) Asks for a charging place by sending a CAM which contains minimum charging time
4) Chooses to select this bus for wireless energy transfer station
5) Book a charging place
6) Drives along the bus for the determined time period in order to recharge

Steps 3-5 constitute the negotiation phase, when MED and EV exchange dedicated short range messages (DSRC) in order to confirm the energy transfer. An assumption that we make is that vehicles can book their charge of battery, as soon as they realize that their charge level is low and a MED meets their criteria on relative distance and available energy.

The architecture of the proposed mobile energy dissemination architecture is demonstrated in figure 1.

D. LTE system description

For the LTE system, we assume that vehicles are equipped with The Evolved Universal Terrestrial Radio Access Network (EUTRAN) interface which enables the vehicles communication to the eNB so as to access the core components of the LTE. LTE Evolved Node B (eNB) base station transceivers are deployed alongside the road network in order to cover the area. Each bus communicates to the LTE the scheduled trip that is going to be followed, the available charging capability and energy value similar to IV C system and charging availability. All vehicles are assumed to be equipped with GPS.

EV that needs energy,
1) Checks whether MED is on his route or not according to their current positions and destinations
2) Checks whether the CC level is high enough in order to cover its energy needs
3) Checks whether the MED is already fully booked
4) Book a charging place
5) Drives along the bus for the determined time in order to recharge

The architecture of the proposed mobile energy dissemination architecture is demonstrated in figure 2. The benefits of such an approach are threefold: First we utilize existing cellular infrastructure. Second we offload 802.11p network from the overhead introduced by frequent communication between EVs and MEDs. Also information is more up to date than that the one received through IVC, where many intermediate nodes may be needed in order to effectively disseminate data. However, vehicles are required to have two types of interface cards and packets that pass through the LTE core are potentially experiencing more delay.

IV. OPEN ISSUES AND RESEARCH DIRECTIONS

There are many remaining open challenges to making this charge transfer network feasible. Aside from the need to have busses equipped with IPT devices for fast and effective energy transfer between mobile nodes, healthy and safety concerns related to the leaking magnetic flux arise. The proposed dynamic wireless charging must comply with the standards on magnetic emissions, that deal with maximum distance and power of transmitted energy. Current solutions include aluminum metal shields in order to shield the interior of the car, but pedestrians and other commuters of the streets like cyclists must be also protected. Inductive Power Transfer (IPT) must now cope with new challenges like small contact area, fast moving nodes, simultaneous charging of many nodes, interference etc.

Drivers that book a charging place on a mobile energy disseminator will need to change their route and follow or drive in front of a bus for some time, probably leading to density fluctuations in Traffic flow. Vehicles that book a charging place on a MED can create clusters according to [22] where mobile charging stations will play the role of the clusterheads.

A combination of dynamic charging architectures, e.g. inductive charging strips, public lighting infrastructures and V2V energy transfer, along with the correct placement of static charging stations would make the dynamic charging more efficient. Intelligent transportation systems on the other hand can play a major role in the evolution of current urban environments to future smart cities, interconnecting different technologies. Innovative eco-routing protocols for EVs over IVC or LTE have to be developed in order not only to reduce energy consumption but also to route vehicles to energy points/paths where inductive recharging can take place avoiding major detours and the creation of traffic jams due to increased vehicular gathering.

Designing of pricing strategies is an open issue in electric vehicle charging. Dynamic pricing can be used in order to shift drivers charging periods in order to exploit at the best the day-by-day predictable solar and wind energy sources making electric vehicles greener. On the other hand for the cooperative systems presented in this article dynamic pricing can be used in order to discourage or encourage drivers from selecting a
particular MED according to the policy of the company such as minimum relative distance, maximum charging power etc.

In the future we are going to conduct simulations in order to determine the feasibility of our cooperative mechanisms and evaluate their efficiency in terms of energy transfer, mean travel time and total distance.

V. CONCLUSIONS

Smart cities of the future are connected cities. Combination of technologies give the possibility to solve problems and extend the use of road users. Vehicles can be interconnected not only for the exchange of information but also for the transfer of energy from and to the smart grid and with each other. As technology goes ahead, new capabilities arise and the interconnection of all ‘road actors’ becomes a reality.

Road transport is the second biggest source of CO2 emissions in the EU after power generation. In order to reduce the negative effects of climate change electric vehicles become more and more necessary. With the penetration of EVs in the market new issues arise that have to be addressed. Charging of vehicles and the connection with the grid is a major issue that demands smart solutions. Combining modern communications between vehicles and state of the art technologies on energy transfer, vehicles can extend their travel time without the need for large batteries or extremely costly infrastructure.

REFERENCES


