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Route Optimization of Electric Vehicles Based on Dynamic Wireless Charging

DIMITRIOS KOSMANOS[1], LEANDROS A. MAGLARAS[2], (Senior Member, IEEE), MICHALIS MAVROVOUNIOTIS[3], SOTIRIS MOSCHOYIANNIS[4], ANTONIOS ARGYRIOU[1], (Senior Member, IEEE), ATHANASIOS MAGLARAS[5], (Member, IEEE), AND HELGE JANICKE[2]

[1]Department of Electrical and Computer Engineering, University of Thessaly, 382 21 Volos, Greece
[2]Department of Computing Technology, De Montfort University, Leicester LE1 9BH, U.K.
[3]KIOS Research and Innovation Center of Excellence, Department of Electrical and Computer Engineering, University of Cyprus, 1678 Nicosia, Cyprus
[4]Department of Computer Science, University of Surrey, Guildford GU2 7XH, U.K.
[5]Department of Electrical Engineering, Technological Educational Institute of Thessaly, 411 10 Larissa, Greece

Corresponding author: Helge Janicke (heljanic@dmu.ac.uk)

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ABSTRACT One of the barriers for the adoption of electric vehicles (EVs) is the anxiety around the limited driving range. Recent proposals have explored charging EVs on the move, using dynamic wireless charging which enables power exchange between the vehicle and the grid while the vehicle is moving. In this paper, we focus on the intelligent routing of EVs in need of charging so that they can make most efficient use of the so-called *mobile energy disseminators* (MEDs) which operate as mobile charging stations. We present a method for routing EVs around MEDs on the road network, which is based on constraint logic programming and optimization using a graph-based shortest path algorithm. The proposed method exploits inter-vehicle communications in order to eco-route electric vehicles. We argue that combining modern communications between vehicles and state of the art technologies on energy transfer, the driving range of EVs can be extended without the need for larger batteries or overtly costly infrastructure. We present extensive simulations in city conditions that show the driving range and consequently the overall travel time of electric vehicles is improved with intelligent routing in the presence of MEDs.

INDEX TERMS Constraint solving, dynamic wireless charging, electric vehicles, inductive power transfer, optimization, vehicular communications routing.

I. INTRODUCTION

There is an increasing interest among government agencies, research institutions and industry around the globe in improving urban living while reducing the environmental impact. The term *smart city* has been coined to describe the city of tomorrow in which modern intelligent technologies, such as IT communication systems, sensors, machine learning, data analytics, come together to provide better services to the citizens. Just like a complex system, a smart city can monitor, coordinate and manage information, connectivity and assets that citizens need every day and adapt to accommodate their demands. One of the basic components of this environment is envisaged to be the next generation of vehicles that combine new sensing, communication and social capabilities. By providing mobile wireless sensing and communications, vehicles can facilitate data access, which is fundamental to realizing the premise of smart cities.

Smart vehicles are expected to be a part of a Vehicular Ad hoc NETwork (VANET), a mobile ad hoc network of cars that has been proposed to enhance traffic safety and provide comfort applications to drivers. A VANET has some unique characteristics such as high mobility of nodes, while cars must follow predefined routes; messages that come from several applications, with different priority levels; high interference, in a noisy environment, and so on. Using the on-board unit, vehicles can communicate with each other as well as with road side units (RSUs) enabling smart application solutions but also enhanced road safety and traffic management. According to several works, e.g., see [1], smart vehicles exhibit five features: self-driving, safety driving, social driving, electric vehicles and mobile applications. In this paper, we focus on electric vehicles.

One of the prohibiting factors for the adoption of the Electric Vehicles (EVs) across Europe is the driving range [2], [3]. That is, the range the vehicle can cover before it needs to be recharged. The lack of supporting charging infrastructure is a pivotal prohibiting factor. The deployment of charging infrastructure is a hard problem [4] as it inadvertently requires changes to the existing civil infrastructure and these are costly and take a long time to implement. The car industry is experimenting with larger and more powerful batteries - new Tesla and Volkswagen (VW) EVs have been released with powerful batteries that promise to cover up to 400km without intermediate charge. However, it is argued that in the future batteries of reduced capacity should be used, mainly for environmental reasons.

It arises the need for new approaches to charging electric vehicles that overcome the lack of supporting infrastructure and the difficulty of adapting the existing civil infrastructure, i.e., road network, without requiring new batteries that take up most space in the car and are not environmentally friendly. *Dynamic wireless charging* is a technology that is still in the R&D phase. A number of companies are actively developing dynamic wireless charging solutions, both in the research and testing phases. BMW has already demonstrated wireless charging with the i8 model. Tesla motors also has already produced the Plugless Model S that can use wireless inductive charging at home. Wireless charging can be the key enabler for electric vehicles if they are to surpass the convenience of gas cars [5]. Preliminary analysis, e.g., see [6], suggests that even the most far-out ideas around wireless charging may become reality sooner than most expect. Qualcom in [7] introduces Wireless Electric Vehicle Charging (WEVC), which is a simple, no fuss solution for charging Electric Vehicles (EVs). Qualcomm Halo WEVC technology uses resonant magnetic induction to transfer energy between a ground-based pad and a charging pad on the electric vehicle. The WEVC proposes expensive charging pad that need to be installed at the surface of a road track. On the other hand, our proposed dynamic charging model uses ordinary city buses as energy sources on the move.

This drives the investigation towards integrated solutions that allow EVs to charge on the move. In [8] and [9], Maglaras *et al.* have proposed a novel idea for increasing the driving range without requiring a significant change in existing road infrastructure. The idea builds on deploying buses and heavy goods vehicles (HGVS), large goods vehicles (LGVs) or trucks, as mobile charging stations, the so-called *Mobile Energy Disseminators* (MEDs) [8]. While a bus is moving along its normal route an EV in need of charging attaches itself to it and charges via wireless power transmission, as shown in Fig. 1.

The buses that take the role of MEDs are ordinary city buses that follow their predefined routes at the roads of the city. We do not use extra buses or trucks as dynamic energy disseminators that could have as a result the occupancy of one

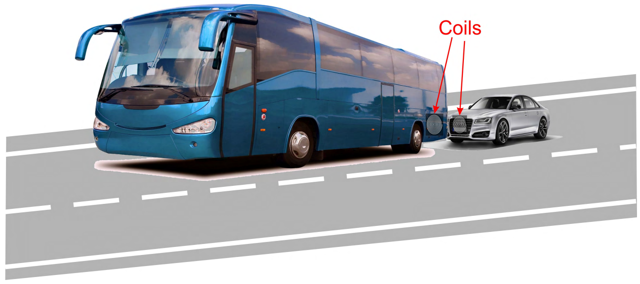


FIGURE 1. Wireless charging of EV using spiral coils.

driveway and the increase of the burden on the road traffic conditions. Buses (inner city) repeatedly move at prescribed routes that are scheduled well in advance. Hence, the EV can meet them by appointment at specific locations. The process is similar to charging of aircraft in flight. When the bus finishes its round trip or its energy inventories are depleted, it will return to the fixed static charging station where it will either fully charge or change the batteries.

In this paper, the focus is on describing the mechanics of the proposed dynamic wireless charging of EVs and the challenges that arise. An EV in need of charge would typically have a choice of MEDs to which it could attach itself. The main contribution of this paper concerns the intelligent routing of EVs in need of charging using a MED or a SCS, and more specifically a solution that draws upon constraint logic programming (CLP) and a graph-based shortest path algorithm (cf Section IV). The optimization problem of (re)routing is considered under a range of criteria and priorities. The objective of the problem is to route a set of EVs in the best possible way, with optimization criterion the waiting time for static charging from a SCS or for dynamic charging from a MED with target the minimum overall travel time, as is depicted in the flow chart of Fig. 2. This procedure is described in detail in Section V-B.

Extensive simulations were conducted in city conditions in order to evaluate the proposed "on the move" charging technique (cf Section V). With different initial energy conditions for all the EVs of the simulation, two different charging systems are compared: one uses a static charging station (SCS) only and the second combines a SCS with a MED. The experiments show that the driving range and consequently the overall travel time is improved by about four times in the dynamic charging system involving MEDs.

This paper proposes a dynamic wireless charging method for EVs using the city buses as MEDs. Our proposed technique is the first in literature according to our knowledge that uses the ordinary city buses and trucks for recharging needs of EVs without any extra infrastructure. This paper makes the following contributions:

- A dynamic wireless method is proposed for the charging of the EVs on the move. This method uses existing city buses as MEDs, without the need for underground or other infrastructure;

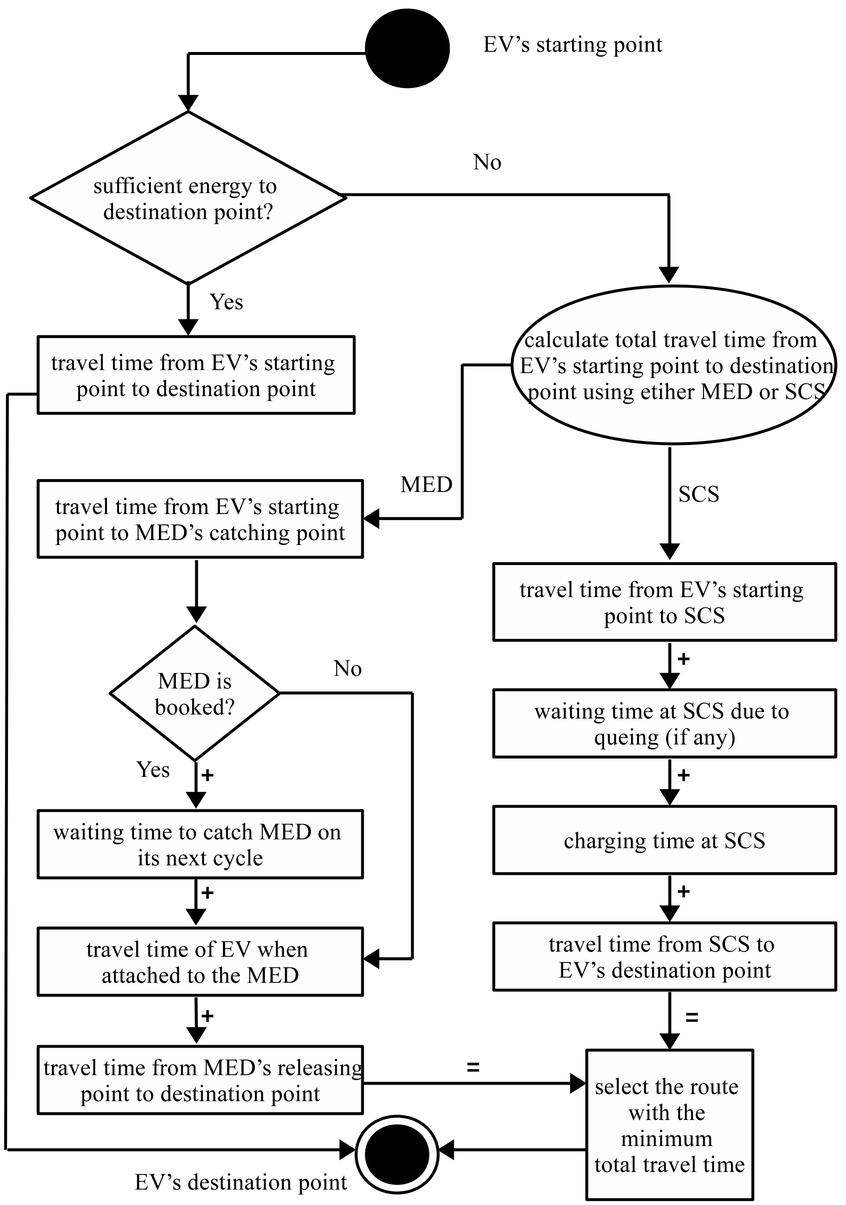


FIGURE 2. **Overall flow chart for the MED or SCS selection and travel time minimization.**

- Our proposed dynamic wireless charging method is based on wireless V2V communications and uses a route optimization solution. The usage of the wireless communication among EVs and MED coordinates the real-time booking procedure for either the SCS or the MED, optimizing the waiting time;
- CACC technology for the MED - EV synchronization during the time that EV follows the MED is used;
- In addition, we show that vehicles can extend their travel range using a real-time Energy exchange that can be facilitated by a (IPT) process.;
- Combining static charging stations with Mobile energy disseminators that can be used for dynamic charging in motion, the overall travel time can be improved about four times compared with the use of only static stations.
- Our intelligent route search method takes into account the waiting time either for the MED - EV appointment or for the waiting time at the queue of SCS. We show that our method decreases significantly the waiting time for the charging procedure and the charging time that is needed for an EV, because the EV is charging when it continues its route;
- The improvement of travel time and driving range of electric vehicles comes with a negligible cost in travel distance. Starving vehicles do not have to stop or make

long re-routes to find a stationary station and recharge their batteries;

The remainder of the paper is organized as follows. Section II discusses related work and places the research within that of the wider community. Section III introduces the key concepts and the overall architecture of the proposed system. Section IV presents the problem formulation of routing electronic vehicles given the presence of static and mobile stations. Section V presents simulation parameters, describes the evaluation of the method and discusses economic benefits of the proposed method. Section VI concludes the article.

II. RELATED WORK

The wireless power transmission technology is being applied for a number of years now in many areas of electrical appliances, like speakers, music and sound transmission generally, alarm systems, electric bells, and electrical facilities of low power in general. In the field of wireless charging of electric vehicles, there are many architectures and special experimental systems that have already been proposed, built and implemented (e.g. Korea reports [10]). In some of these infrastructures the locations (points) used for charging are either fixed (static stations) installed either under the surface of streets and in other public locations (i.e. garages) or on lightning columns [11], [12] on the road side. Specifically, regarding the underground electric coils installed under the surface of streets, KAIST proposes a new design concept for an alternate electric car-On-Line Electric Vehicle (OLEV) [13]. OLEV draws its electric power from underground electric coils without using any mechanical contact. But, a great concern using these approaches is the electromagnetic field exposed to the people that move around these streets. OLEV has also a small battery, which enables the vehicle to travel on roads without the underground electric coil. Batteries are recharged whenever OLEV draws electric power from the underground coils and thus, do not require expensive separate charging stations. However, above technology can be effective if about 30% of the roads in Seoul have the underground electric power coil, which is quite costly. The wireless power transmission in the proposed system is achieved using the Tesla coil method, with spiral coils installed on the vehicles.

Previous work on charging electric vehicles mainly focuses on static charging stations [14], swappable batteries [15], eco-routing of vehicles [16] or dynamic charging [17] that is based on static sources. In [18] a routing strategy for vehicle charging called ''Charging Station Strategy - Vehicle Powertrain Connected Routing Optimization (CSS-VPCRO)'' is proposed. This approach constitutes solving an iterative least cost vehicle routing process, which utilizes the communication of electrified vehicles (EVs) with competing charging stations to exchange data, such as electricity price, energy demand, and time of arrival. EV routing problem is solved to minimize the total cost of travel using the Dijkstra algorithm with the input from EVs battery management system, electricity price from charging stations, powertrain component efficiencies, and transportation network traffic conditions. In [19] a route search method for electric vehicles (EVs), which calculates the minimum travel time that includes necessary stops to static charging stations, is proposed. The above method uses only static charging stations in which the electric vehicles must stop for charging. On the other hand, we provide the possibility of dynamic wireless charging of an electric vehicle on the move, following a MED for a part of its predefined route at the roads of the city. Our method introduces for the first time in the literature the concept of Mobile Energy Disseminators that can take the role of energy sources and can operate along with static charging stations in order to decrease the overall waiting time before the charging procedure begins and the charging time that is needed for an EV. Based on the work in [17] dynamic wireless charging of vehicles promises to partially or completely eliminate the overnight charging of electric vehicles through the use of dynamic chargers that may be installed on the roads to keep the vehicle batteries continuously charged, thus making electric vehicles more attractive. The use of dynamic wireless charging may increase driving range and reduce the size of the battery pack of an electric vehicle. On the other hand, this leads to increased safety concerns and infrastructure costs.

Previous work on dynamic wireless charging has not considered the solution of moving energy charging stations that can charge vehicles, which are also on the move, in order to reduce the range anxiety and increase the reliability of EVs. Mario *et al.* [11] presented a solution called *Telewatt* that involves the reuse of existing public lighting infrastructure for vehicle charging. It does so by exploiting the excessive power of the lamps mostly at night. This system that supports wireless charging between the infrastructure and the moving vehicles raises health issues related to the leaking magnetic flux. In [20] Ning *et al.* present a system that can charge vehicles through inductive coupling. In [21] a non-radiative energy transformer that can perform efficient wireless energy transfer, commonly referred as Witricity and based on ''strong coupling'' between two coils which are separated physically by medium-range distances is investigated. The prototype for EV that was developed at Oak Ridge National Laboratory (ORNL) in the United States achieved efficiency of nearly 90% for 3 kW power delivery. However, systems that are based on inductive coupling between the grid and a moving car can cause power pulsations in the vehicle battery and the grid supply. This can result in deterioration on the battery service life of EVs as well as a drop on the power quality of the grid [22].

The disadvantages of these methods can be summarized as follows.

- Charging an EV from a stationery charger introduces a large or small delay due to
  1) the change of the route of the movement of the EV to the loading point (location),
  2) the need of parking for a sufficient period of time to charge, and
  3) the restoration of the EV at the initial route.

- The infrastructure would need to be extensive and consequently expensive [23]
- The (energy transfer efficiency) performance of the charging method would be relatively insufficient (or low) due to the inherent operational difficulties of the systems (e.g., distance, parallelism, etc.)

The solution we propose in this paper builds on the use of inner city buses as MEDs, hence it does not suffer from the pitfalls associated with static charging stations. In addition, it uses buses or trucks for the dynamic charging, so predefined moving charging stations which have predefined scheduled routes along the existing road network, rather than vehicle-to-vehicle (V2V) charging schemes that have been discussed in the literature [24].

The EVs attach themselves to one or more MEDs during some part of their journey and until they have enough energy to reach their destination (or get to the closest static charging station). In this way, electric cars are charged "on the fly" and their range is increased while moving along the road. Hence, our proposal does not require significant changes to the existing road network and civil infrastructure [11], [25], [26] and, unlike other proposals [27], does not pose any health hazards.

III. DYNAMIC CHARGING AND MOBILE ENERGY DISSEMINATORS

The dynamic wireless charging system is based on the combination of vehicular communications and inductive power transfer (IPT) among the energy carriers and the electric vehicles. IPT allows efficient and real-time energy exchange where the vehicles involved can play an active role in the procedure.

A. ENERGY TRANSFER VIA IPT

Using the IPT wireless method, a 10-minute charge would provide a driver with an energy charging of 3 - 8 kWh of electric energy, which is equivalent to about 9 - 23 miles travel distance. The United States fuel economy estimates that 35 kWh energy charging equals with 100 miles travel distance. The energy charging 3 - 8 kWh requires 20 - 50 kW charging rate from the moving charging stations (see Table 1). This travel distance corresponds to 30 - 78 percent of the drivers average daily travel distance. In real-world terms, that means typical urban American drivers could cover 78 percent of their average daily travel of 23 miles on a 10-minute charge with charging rate 50 kW. European drivers fare even better; a 10-minute charge with charging rate 50 kW under this wireless scenario would cover nearly two days of a typical European's driving habits, which amounts to about 20 kilometers or 12.5 miles per day [28].

In the case that the charging rate would be 20 kW, a 10-minute charge would cover about 9 miles or about 15 kilometers. By comparison, a public 30 amp wired charging station provides electric cars with just 3.7 miles of range on a 10-minute charge; it takes about an hour at a typical public wired charging station to provide just 22 miles of range to an electric car.

TABLE 1. Miles per 10-minute charge for electric cars [29] *This is for a 30 amp public charging station.

Method	Value
Tesla Supercharger	56.7
Mobile Energy Disseminator (MED)	22.85
Public Charging Station*	3.7

B. EVS AND MEDS IN A VANET ARCHITECTURE

The use of mobile nodes as relay nodes is common in vehicular ad hoc networks (VANETs). In a VANET, mobile nodes can serve as carriers or disseminators of useful information [30]. Defining influential spreaders, nodes that can disseminate the information to a large part of the network effectively, is an open issue in ad hoc networks [31]. In VANETs, nodes with predefined or repeating routes that can cover a wide range of a city region can play the role of roadside units in terms of message dissemination. By exploiting their mobility these disseminating nodes can provide even higher quality-of-service (QoS).

Following a similar approach the proposed dynamic wireless charging system is using special nodes, buses or trucks, that act as energy sources to EVs that are in energy need. The architecture of the proposed system is shown in Fig. 3. These vehicles, which are called MEDs, use electric plug in connection or IPT in order to refill starving EVs. Buses can play the role of MEDs in urban environments, since they follow predefined scheduled routes and their paths cover a major part of a city, while trucks can play the role of energy chargers mainly on highways. Buses can be fully charged when parked, before beginning their scheduled trip, and can be continuously charged along their journey by IPT stations installed at bus stops (See Fig. 3).

EVs follow the MED for a part of its route in order to perform dynamic wireless charging. Specifically, vehicles follow the MED with the same speed while charging, using the Cooperative Adaptive Cruise Control (CACC) technology [32]. CACC is an enhancement of Adaptive cruise control (ACC), which is based on sensor data. It leads to tighter following gaps between EV - MED and faster response to velocity changes compared to ACC, and makes collaborative driving such as platooning feasible [33]. Using the CACC technology, vehicles that book charging places on the same MED can create clusters/platoons where the MED will play the role of the clusterhead [34]. The wireless communication that is needed for motion synchronization between EV and MED is carried out with beacons that are periodic single-hop messages.

The buses or trucks (MEDs) run on electric power. They will have battery systems for their movement, which are used exclusively by the bus or truck (MED). At the same time they carry other systems of special batteries with more energy, which will only be used for charging of EV vehicles

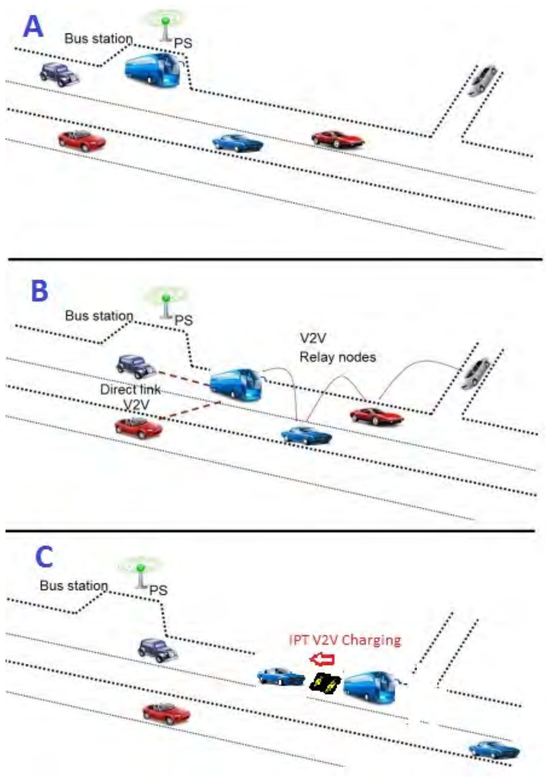


FIGURE 3. Application example of a Mobile Energy Disseminator: In A, Contactless Wireless-Consistency charging is used to deliver charging to a bus; in B, V2V communication between MED and EV; in C, EV recharges from the bus using IPT.

in motion. The energy of these batteries will be able to cover the energy need of several EVs. The total energy of the charging batteries of the bus is expected to be greater than 200 kWh. The energy of the batteries of an ordinary EV is about 50 kWh, hence the amount of the energy of the batteries carried by the bus will be capable to serve 4 EVs for a total recharge and more for partial recharges. The charging rate will be 20-50 kW (cf. Section 1), so that the required charging voltage shall be relatively low. Finally, the bus or truck will carry the mechanisms necessary for the connection and transfer of energy from the MED to the EVs. The EV charging process will be as follows.

1) EV contacts MED and makes an appointment (time, location).
2) EV drives near the MED and creates a platoon with it to initiate the charging process.
3) The MED charges the EV via a loose connection device consisting of 2 coils, of plain form or better of spiral conical form for greater efficiency and ease of connection. These coils can be of different diameter and perhaps even of different numbers of turns. Another solution comprises using 2 coils, one of which with larger diameter which is mounted on the EV and the other with the smaller diameter on the MED. E / M Shielding will be available on all 2 vehicles. The 2 coils will be properly covered, and will be uncovered during the charging process.
4) Vehicles come close and using wireless communication, like an advanced cruise control system, controlled for safety reasons by the MED and while in motion, come in such a position that the smaller diameter's MED coil comes close enough to or enters in the EV coil.

In this article we investigate the wireless power transfer via a loose connection device consisting of 2 coils, of plain or conical form. Due to the design of the coils, and the very close position between them, the energy transfer efficiency will be more than 90%. The proposed design has a similar functionality with the typical Tesla coils [35], or Rogowski Coil [36]. With this solution, electric power is transferred to the vehicle through an electrically generated magnetic field. The basic functionality of the charging process is comparable to charging via a cable. An innovative, induction-based mechanism that is developed by Siemens eCar Powertrain Systems [37] can be also used to offer a significantly higher degree of convenience, when compared with charging via a cable.

A major concern when dealing with strong magnetic fields, such as those used in wireless power transfer, has to do with the impact on living organisms. By only turning on the coils when a compatible electric vehicle is over the primary charging pad, the charging system eliminates the possibility that a person or animal could be affected by the strong fields created. Another issue with safety has to do with the presence of metal objects at or close to primary charging pads. These objects can cause hazardous conditions and can interfere with WPT. To address this problem, a foreign object detection system can be deployed in future to determine when objects are on top of the primary coils. In such situations the system will not energize the transmitting coil so as to avoid damage to the vehicle and/or charging system.

C. COMMUNICATION AMONG ENTITIES

To state its presence each MED or SCS periodically broadcasts cooperative awareness messages (CAM). Each beacon message consists of a node identifier (Vid), node location, scheduled trip (a subset of set L), current charging capability (CC) and energy value (E=kWh), the queue time at SCS or waiting time (wt) at MED appointment point and the speed value of the MED. CC is the current energy that the mobile charging station can afford to dispose of to charge the vehicle without jeopardising its own needs. These messages are disseminated by all vehicles that effectively act as relay nodes.

IV. ROUTING EVS IN NEED OF CHARGING

A. PROBLEM FORMULATION: CONSTRAINED SHORTEST PATH

The problem of routing EVs can be presented using a directed weighted graph. Let $G = (N, A)$ be a weighted graph where N is a set of points, e.g., road intersections or Static Charging Stations (SCS) and $A = \{(i, j) \mid i, j \in N, i \neq j\}$ is a set of arcs (links) connecting two points. SCSs are defined as

TABLE 2. Mathematical symbols used in this paper.

Symbol	Description
$G=(N,A)$	Weighted graph
N	Set of points
A	Set of links
(i,j)	Link between points i and j
dt_{ij}	Drive time between points i and j
c_{ij}	Energy consumed between points i and j
ρ	Induced energy
S	set of static recharging stations
S'	extension of S that represent multiple visits
M	set of MED points
M'	extension of M that represent multiple visits
$SW_i(t)$	SCS i waiting time at period t
$MW_i(t)$	MED point i waiting time at period t
k	EV id
K	set of EVs
s^k	start point of an EV
e^k	destination point of an EV
Q^k	energy capacity of EV k
ϵ_i^k	energy level of EV k at point i
x_{ij}^k	binary decision variable to identify the route of EV k
y_{ij}^k	binary decision variable to identify path where EV k received energy from a MED
z_i^k	binary decision variable to identify if an EV k received energy from SCS i
q_i^k	binary decision variable to identify the MED point an EV k has attached to receive mobile energy
ct_i	charging time at SCS i
wt_i	waiting time at SCS i or MED point i
v	number of SCSs
u	number of MED points

$S=\{s_0,\ldots,s_v\}$ and a set of dummy nodes that represent possible multiple visits to the same static recharging station is defined as $S'=\{s_{m+1},\ldots,s_{m+h}\}$ such that $S\cup S'\subseteq N$. Each SCS i is associated with a waiting time wt_i.

An EV can also receive energy by MEDs that visit a predefined cyclic route of MED points $M=\{m_0,\ldots,m_u\}$. Similarly with the SCS, a set of dummy nodes may represent possible multiple visit to the same MED point defined as M' such that $M\cup M'\subseteq N$. An EV can attach to a MED at any point in its route and start charging. Note that the charging rate of MED is always higher than the consumption rate. Similar with the SCS, each MED point i has a waiting time wt_i This is because an EV may need to wait to a point until a MED is available or arrives. MEDs and SCSs accept/reject demands of EVs in an intelligent way, i.e., to minimize the route of the vehicles at the best possible way or to distribute energy at the best possible way (defined by the communication system).

Each arc $(i,j)\in A$ is associated with a non-negative travel time $dt_{ij}\in\mathbb{R}^+$ and a non-negative energy needed to travel $c_{ij}\in\mathbb{R}^+$ when points i and j are connected otherwise $dt_{ij}=c_{ij}=\infty$. The weight matrix of the problem is defined as $\mathbf{D}=\{dt_{ij}\}_{n\times n}$.

The objective of the problem is to route a K set of EVs in the best possible way, i.e., minimum travel time. The problem can be formulated as a multiple constrained shortest path problem. Every k-th EV has a battery of Q^k capacity, starting point s^k and destination point e^k. The travel time is defined by the driving (dt), the charging (ct) and waiting times (wt) at different SCS or MED points (if needed). The energy level at point i is defined as ϵ_i^k. Hence, the initial energy level is defined as ϵ_s^k.

Let x_{ij}^k and y_{ij}^k be binary decision variables that define whether EV k passed from point i to j and whether EV k received energy from a MED from point i to j, respectively. Also, let z_i^k and q_i^k be binary decision variables that defines the SCS where EV k received energy and the MED point where EV k attached with a MED, respectively. All variables used in this paper are summarised in Table 2.

The objective to minimize the travel time of EVs is given next:

$$\min \sum_{k\in K}\Big(\sum_{(i,j)\in A,i\neq j}(dt_{ij}x_{ij}^k)+\sum_{i\in S\cup S'}(ct_i+wt_i)z_i^k + \sum_{i\in M\cup M'}(wt_iq_i^k)\Big) \tag{1}$$

$$\text{s.t.} \sum_{j\in N}x_{ij}^k-\sum_{j\in N}x_{ji}^k = \begin{cases}1, & \text{if } i=s^k;\\ -1, & \text{if } i=t^k;\\ 0, & \text{otherwise,}\end{cases} \quad \forall i\in N, \forall k\in K \tag{2}$$

$$x_{ij}^k-y_{ij}^k\geq 0,\quad \forall k\in K,\ \forall j\in N,\ \forall i\in N, i\neq j, \tag{3}$$

$$\epsilon_j^k\leq\epsilon_i^k-(c_{ij})x_{ij}^k+(\rho_2 d_{ij})y_{ij}^k x_{ij}^k+Q^k(1-x_{ij}^k),\quad \forall k\in K,\quad \forall j\in N,\ \forall i\in N,\ i\neq j, \tag{4}$$

$$\epsilon_i^k\geq 0,\quad \forall k\in K,\ \forall i\in N, \tag{5}$$

$$\epsilon_i^k\leq Q^k,\quad \forall k\in K,\ \forall i\in N, \tag{6}$$

$$\epsilon_i^k = Q^k z_i^k, \quad \forall k \in K, \ \forall i \in S \cup S', \tag{7}$$

$$\epsilon_i^k \geq c_{ij}, \quad \forall k \in K,$$
$$\forall i \in N, \exists j \in S \cup S' \cup M \cup M', i \neq j, \tag{8}$$

$$x_{ij}^k, y_{ij}^k \in \{0, 1\}, \quad \forall k \in K, \ \forall i \in N, \forall j \in N, i \neq j, \tag{9}$$

$$z_i^k \in \{0, 1\}, \quad \forall k \in K, \ \forall i \in S \cup S', \tag{10}$$

$$q_i^k \in \{0, 1\}, \quad \forall k \in K, \ \forall i \in M \cup M', \tag{11}$$

where ct_i is the charging time from a charging station or visit i (for a MED the charging time is already embedded to the tour in (4), and wt_i is the waiting time at charging station (or a MED's point) i.

Constraint (2) ensures flow conservation of the route; constraint (3) ensures that whenever an EV receives energy from a MED while moving always consumes energy; constraint (4) ensures that an EV has enough energy to move to the next point (including MED's points); constraint (5) and (6) ensures that energy level never falls under zero or exceeds its capacity; constraint (7) ensures that an EV is fully charged at static energy station; constraint (8) ensures that an EV has enough energy to reach at least one recharging static station or MED point.

The feasibility of an EV k route can be identified by the current energy level and the total energy needed for the route such that energy must not be negative, as follows:

$$\epsilon_s^k - \left(\sum_{(i,j) \in A} c_{ij} \right) + \rho \geq 0 \tag{12}$$

where ϵ_s^k is the initial energy level, c_{ij} the energy consumed from points i to j and ρ is the induced energy.

The key differences of the proposed shortest path problem (described above) with the traditional shortest path problem are:
a) multiple shortest paths are required, and
b) energy constraints are imposed
The proposed problem is more challenging and realistic because not all shortest routes are feasible due to the energy constraints; see (12) and also one shortest route may affect the remaining shortest routes. For example, if an EV is currently charging at a SCS; then the other EVs will possibly have to wait (i.e., increasing the queue time of the SCS) or find a shorter route via another SCS.

B. SOLUTION METHOD

Since the problem is a shortest path problem it can be solved by several existing optimization algorithms efficiently (i.e., in polynomial time). In this paper, we consider the well-known Dijkstra's algorithm [38] to calculate the shortest route, e.g., minimize the travel time in Eq 2, for EV k from its starting point s^k to its destination point e^k. However, the problem has several constraints that need to be addressed and by simply using the Dijkstra's algorithm from s^k to e^k may result to an infeasible route, i.e., (12) does not hold.

The key idea of the proposed solution method is to initially check whether the route calculated by Dijkstra's algorithm satisfies (12), meaning that it has sufficient energy to reach the destination. If the route is feasible then the EV should begin its route without any energy recharging consideration. Otherwise, it needs to find a point, either static or moving, to recharge its battery in order to have sufficient energy to reach the destination as shown in Algorithm 1.

Algorithm 1 FindShortestPath(k,s^k,e^k)

```
1:  INPUT EV information, e.g., id, source and destination
2:  FinalRoute^k ← Ø          % final route of k EV
3:  T^k ← 0                   % travel time of k EV
4:  R^k ← Dijkstra(s^k, e^k)  % partial route of k EV
5:  if (R^k is feasible) then
6:     FinalRoute^k ← R^k
7:  else
8:     p ← FindBestEnergyPoint(s^k)
9:     FinalRoute^k ← Dijkstra(s^k, p) ∪ Dijkstra(p, e^k)
10: end if
11: T^k ← Cost(FinalRoute^k)
12: OUTPUT FinalRoute^k % feasible route to travel verified
    by (12)
13: OUTPUT T^k % travel time using (2) but for a single EV
```

For this case Dijkstra's algorithm is used again to find the best point to receive energy from. Since there may be several static charging stations or MED points that the EV can choose, several Dijkstra's calculations are performed, one for each point, and the best one is selected as shown in Algorithm 2. The criteria to identify the best energy recharging point depends on the total travel time, including waiting time, charging time and driving time. In addition, the energy point selected needs to be feasible, i.e., the current energy level of the EV needs to be enough to reach the selected energy point (i.e., constraint (8)). Hence, the energy points that cannot be reached according to (12) are discarded.

Finally, when the energy point is selected the shortest path using the Dijkstra's algorithm is calculated from the selected energy point to the destination. Note that in case this path is still not feasible because the energy level may not be sufficient to travel from the energy point to the destination the process in Algorithm 2 can be repeated from the current position, e.g., the energy point to the next energy point.

V. EVALUATION

To evaluate the effect of the dynamic wireless charging of EVs, we conducted simulations in the city of Erlangen.

A. EVALUATION SETUP

As can be seen in Fig. 4 a bus which follows a specific route (shown in yellow in the Fig.) is used as a MED. On the other hand, a static charging station (SCS) is located at a fixed point at the road side of the corresponding city district. All the parametric side roads of the area in which the SCS and MED charging models are located are used as starting points (s^k) for the dynamic wireless charging system with the

Algorithm 2 FindBestEnergyPoint(s^k)

INPUT current point of EV k
$best \leftarrow \emptyset$ % route of a best energy point
p % best energy point
for ($i \in S \cup M$) **do**
  $R^k \leftarrow$ Dijkstra(s^k, i)
  if (($Cost(R^k) < Cost(best)$) && (R^k is *feasible*)) **then**
    $p \leftarrow i$
    $best \leftarrow R^k$
  end if
end for
OUTPUT p % best energy point

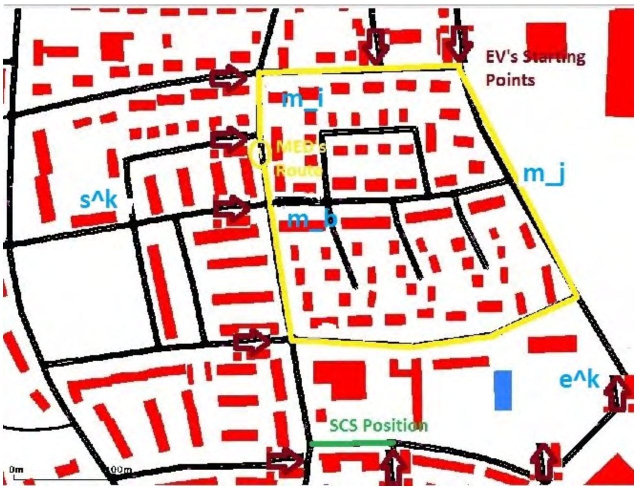


FIGURE 4. Part of the Erlangen city map used for conducting the simulations. The MED route is marked in yellow. The position of the SCS is marked in green. The brown arrows are pointing at the starting points of the journeys of the EVs for both the SCS and the SCS + MED charging system.

same probability. The point at which the EVs are introduced in SCS or MED system is shown in Fig. 4 with (m_b, s_b respectively). The number of EVs that are inserted in the system is between 0 and 100. In addition, each EV k entering the system has starting energy ϵ_s^k according to a uniform distribution with values between $1 - 6\ kWh$.

The only communication paths available are via the ad-hoc network and there is no other communication infrastructure. All the above parameters and the selected evaluated area, as well, were not in favour of any charging method (MED or SCS). The power of the antenna is $Ptx = 18dBm$ and the communication frequency f is 5.9 Ghz. In our simulations, we use a minimum sensitivity (Pth) of $-69\ dBm$ to $-85\ dB$, which gives a transmission range of 130 to 300 meters, as can be seen in Table 3. As a result of the above transmission range, there is no communication with a few EVs. So, a number of EVs are excluded from the charging procedure because of the communication lost among EVs. This happens when the Signal-to-Interference-Ratio (SINR) threshold is below 10 dB due to attenuation that is caused by the building obstacles of the city.

TABLE 3. Evaluation parameters.

Independent parameters	Range of values
Number of vehicles	0-100
Initial Energy (ϵ_s^k)	1-6 kWh
C_{ind}	0.7-0.8
P_{ind}	20-50 kW
P_{tx}	18dBm
f	5.9Ghz
Minimum sensitivity (P_{th})	-69dBm to -85dB
Transmission range	$130 - 300$ meters
n	0.7-0.8

B. IMPLEMENTATION OF THE DYNAMIC CHARGING SYSTEM

As described in Section III-C, all the EVs are informed for the waiting time (wt_i) either by the SCS i or by the MED i through the periodical communication with MEDs or SCS (using the CAM messages). As an example, assume that an EV k is located at point (s^k) as starting point in Fig. 4. In order this EV to decide the best point for the insertion of dynamic charging system the Dijkstra's algorithm is used (i.e. the Algorithm 1). The point (m_b) is the best point for the MED system, while the point(s_b) is the best point for insertion for the SCS system (see Fig. 4).

The value for minimization with our dynamic charging algorithm is the travel time for a vehicle between the starting point (s^k) and the target point (e^k). The total travel time if an EV chooses the SCS choice depends on the travel time between the (s^k,s_b) points, the charging time at the SCS, the waiting time here and the travel time between the points (s_b,e^k), for which the Dijkstra's algorithm is used again. The charging rate level of the EVs at the SCS is about $19, 2\ KW/sec$ [39]. The waiting time at the SCS depends on the queue of the SCS and the driving time between (s^k,s_b) points. Each EV periodically informed by the SCS about the current queue and all the bookings that SCS already has with the Queue (Waiting) time (wt_b) variable. Based on its current distance to SCS and mean velocity it can compute the time that it will arrive to the SCS (Driving time (dt)). So it can compute the waiting time as: $WaitingTime = wt_b - dt(s^k, s_b)$.

If a vehicle chooses the MED for its recharging needs, travel time will be adjusted to reflect the travel time between the points (s^k,m_b), the waiting time of a vehicle at point m_b, the time interval for which this vehicle follows the MED and thus is charged (EV k follows the MED for the roads (i,j) which are defined from the binary variable y_{ij}^k) and the travel time from the last point (m_j) of the last road (i,j), where EV k follows the MED, to the destination point (e^k) with the usage of Dijkstra's algorithm. At the starting point (s^k), each EV at short intervals informed by the MED about its current position (m_i) and the booked road segments that MED already has.

An electric vehicle also computes the closest point (m_b) to meet the MED based on the MED's cycle and the vehicle's current position and the driving time, using mean velocity. Based on the charging coefficient a vehicle computes for how many road segments it needs to follow the MED and that way it can find the ending point (m_j). Based on the booking of the MED, its current position and meeting point m_b, a vehicle computes the waiting time (the time that it will need to wait for the MED to come free of any booking at meeting point (m_b)). If road segments (m_b, m_j) are not booked then the waiting time will be: $wt = dtMED(m_i, m_b) - dtVehicle(s^k, m_b)$.

If the above equation is negative then EV k will have to go for the next cycle of the MED: $wt = dtMED(m_i, m_b) + dtMED(m_b, m_b) - dtVehicle(s^k, m_b)$. If any road segments between (m_b, m_j) are booked then the specific EV will have to go for the next cycle of the MED again. We must add that there is no upper limit on the waiting time of a vehicle until the MED will be available. All the above procedure of the travel time optimization of an Ev is deeply described in Fig. 2.

For the charging time of an EV from the MED, when this EV books the MED then it knows the point (m_i), so it can compute the charging time based on mean velocity and the ending point (m_j) of charging. In order to calculate the energy will be needed for each vehicle, the power consumption for each road traveled must be computed [40]. The energy cost of every road segment can be expressed as a proportion of the mean velocity. The velocity is the quotient of the distance of the road segment and the time that a vehicle will need to spend on this segment (i, j), i.e. $T_{i,j}$, on average. The two forces that oppose the motion of an automobile are rolling friction, F_{roll} and air resistance, F_{air} ([9]).

$$F_{roll} = \mu_\varsigma * m * g, F_{air} = \frac{1}{2} A * C * p * u^2 \tag{13}$$

where, m is the mass of the car in Kg, $g = 9.8 m/s^2$, u is the mean velocity in m/s and μ_ς is the rolling resistance coefficient. C is a dimensionless constant called the drag coefficient that depends on the shape of the moving body, A is the silhouette area of the car (m^2) and p is the density of the air (about 1.2 kg/m^3 at sea level at ordinary temperatures). Typical values of C for cars range from 0.35 to 0.50. In constant-speed driving on a level road, the sum of F_{roll} and F_{air} must be just balanced by the forward force supplied by the drive wheels. The power that a vehicle needs when traveling with a steady speed is given by (14).

$$P = n * F_{Forward} * u = n(F_{roll} + F_{air}) * u \tag{14}$$

where, n is the efficiency factor of the system. The energy cost of vehicle k for traveling in road segment (i, j) in kwh, i.e. c_{ij}, is calculated by (15).

$$c_{ij} = P * T_{ij} \tag{15}$$

If the road segment belongs to the path of a MED, then a vehicle can increase its energy by induction. The amount of the induced energy is proportional to the total time that an EV and the MED will stay connected. This time depends on the meeting point (m_b) between a vehicle and the MED in relation to the total road segment length and the availability of the MED. In order to represent the induced energy per hour to the EV, (15) is rewritten:

$$c_{ij} = P * T_{ij} - \rho \tag{16}$$

In Equation (16) the ρ is the induced energy to the vehicle k and is given by:

$$\rho = t_{cont} * C_{ind} * P_{ind} \tag{17}$$

C_{ind} is the induction coefficient and t_{cont} the time of contact between the MED and the EV. P_{ind} is the power of the MED. The values of the above parameters can be seen in Table 1. We ignore acceleration and deceleration phenomena.

C. STARTING ENERGY VS POWER CONSUMPTION LEVELS

In our simulations, we used 3 levels of recharging needs for the sum of the EVs. The starting energy for each EV is the remaining energy with which they approach the starting points of the system. We consider 3 different levels of the power consumption energy for the EVs in comparison with their initial energy. At the first level of the recharging energy we consider that only the 20% of EVs need recharging in oder to reach at their destination (see Fig. 5a). The second level of the power needs of the EVs is that in Fig. 5c. Here 60% of EVs need recharging, increasing the complexity of the system. Last, at the third level of power need and initial energy comparison almost all the EVs need recharging (the 95% of EVs), as can be seen in Fig. 5e. Contrary to the [3] in which the number of drivers with range anxiety is a fixed number, this number is dynamic in our system and depending on the EVs needs. All the drivers with initial energy smaller than the energy will be needed to be consumed are defined as anxious drivers.

D. SCS VS. SCS + MED

In this section we conduct a comparison of two different charging systems using three scenarios (see Fig. 5a,5c and 5e. The first charging system contains only a static charging station, and the second charging system has a SCS and a MED. In Fig. 5b,5d,5f the travel time results of the above two system are presented that correspond to the charging needs of Fig. 5a,5c,5e, respectively.

Studying these results, it transpires that as the charging needs of vehicles are increasing, the travel time for both systems is also increasing. Specifically at the Level 1 of recharging needs, the travel time using the dynamic charging model (SCS + 1 MED) is smaller at about 2 times than that using the charging system (SCS) (see Fig. 5b). At the Level 2 of recharging needs, the corresponding travel time using the (SCS + 1 MED) model is improved and is now at about 3 times smaller than that using the (SCS) model (see Fig. 5d). Last at the Level 3 of recharging needs, the travel time using the dynamic combined charging model is at about 4 times smaller than that using only the (SCS) model (see Fig. 5f).

Another observation from the results is that the travel time of the (SCS+MED) system is less than the (SCS) for all the

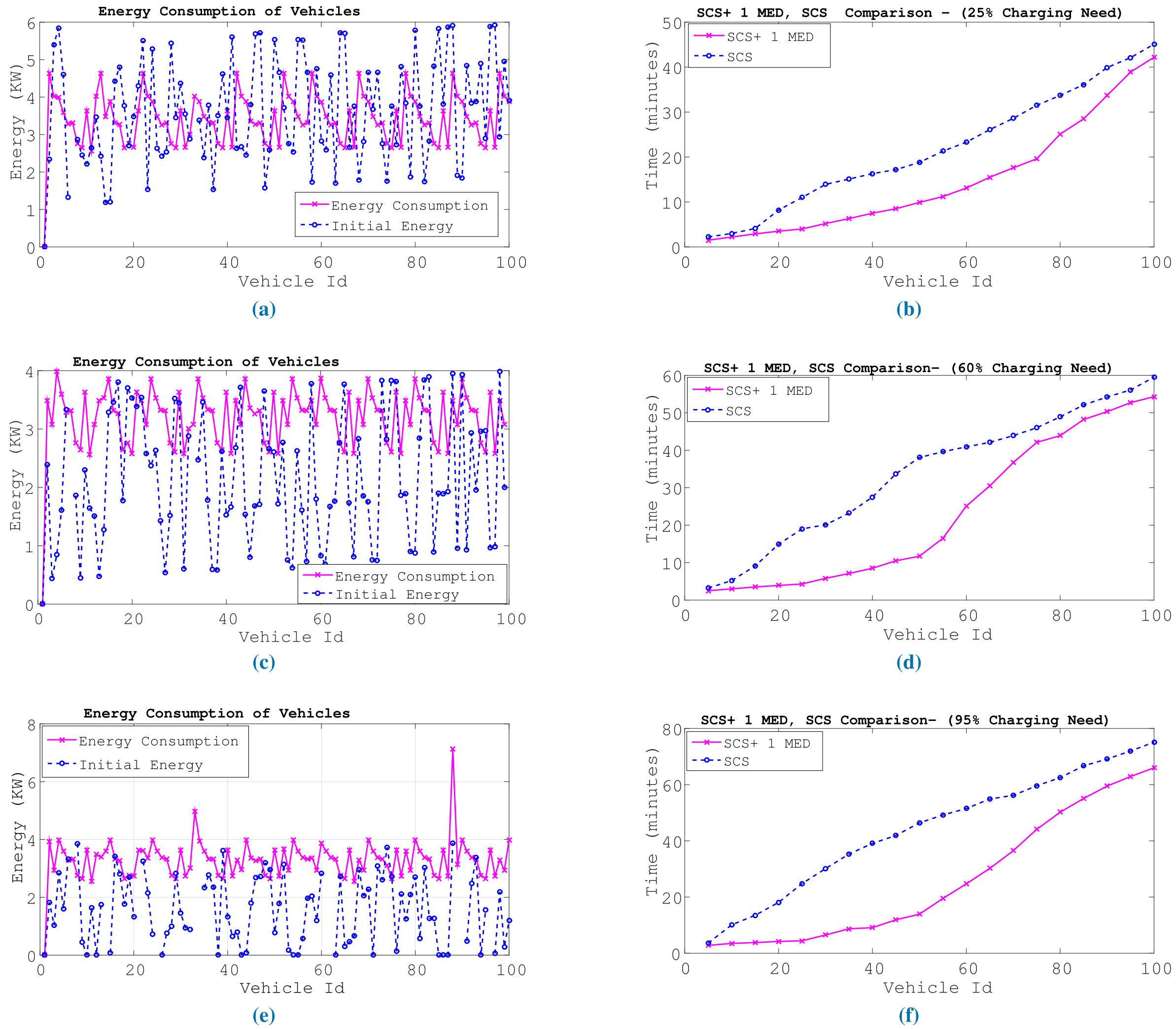


FIGURE 5. **Travel Time of all the Levels of Energy recharging. (a) (LEVEL 1): The 20% of EVs need recharging. (b) Travel Time when the 20% of EVs need recharging. (c) (LEVEL 2): The 60% of EVs need recharging. (d) Travel Time when the 60% of EVs need recharging. (e) (LEVEL 3): The 95% of EVs need recharging. (f) Travel Time when the 95% of EVs need recharging.**

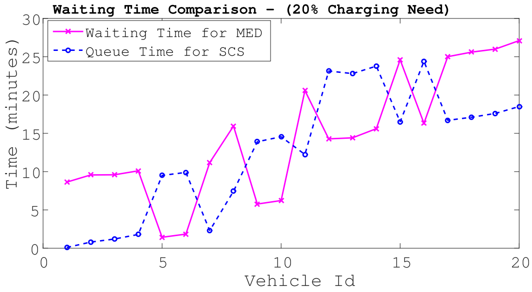
circumstances of anxious drivers (0-100) and energy charging need levels. For a small number of anxious drivers the difference between the two charging systems is very small. As the number of anxious drivers is increasing, the difference between the two systems is increasing too. However, when the number of anxious drivers is above 50 (for the Level 3 of charging needs) the difference is diminished. This behavior is due to the waiting time of the vehicles for the MED for a large number of cycles because of the preceding MED's bookings.

Last, it is obvious that when the number of anxious drivers is above average of overall EVs the need of a MED in addition to a SCS is necessary, because the difference between the (SCS+MED) system and the system that has only one SCS is bigger with (60%, 95%) anxious drivers than that with (20%).

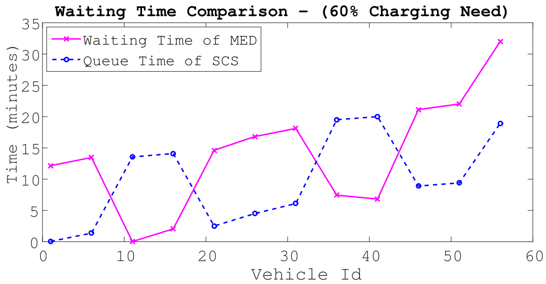
E. SCS + MED SYSTEM EVALUATION

In this subsection the evaluation of the system (SCS + 1 MED) is presented in more detail. In Fig. 6, the waiting time (wt) of each EV at the point (m_b) that is planned to meet and follow the MED is compared with the queue time for each EV at the SCS. Moreover, in Fig. 7 the percentage of EVs that select the MED or the SCS for recharging is presented. We can see that as the number of anxious drivers is increasing, the number of EVs that select the MED as energy disseminator is increasing too.

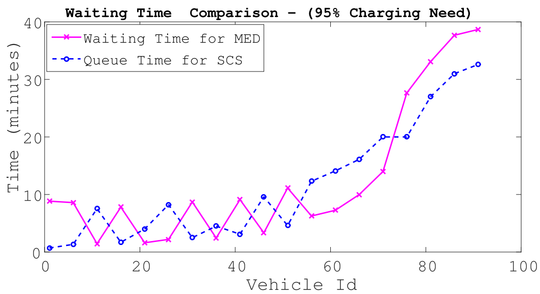
Studying more carefully Fig. 6, it is obvious that at the starting time of the dynamic charging system when the queue of the SCS is empty and due to the fact that all EVs select the MED for recharging results on the increase of the waiting time. As the simulation time increases, the waiting time for MED and the queue time for SCS both rises and falls irregularly. This happens because the choice of EVs (MED or SCS) for recharging are quickly interchanged. Studying the travel time of Fig. (5a,5c,5f), a reduction of the difference of the travel time between the systems (SCS),(SCS + 1 MED) has observed. This phenomenon can be explained due to the increase of the waiting time at the MED, because of the frequent MED selection, (see Fig. 6) when the number



(a)



(b)



(c)

FIGURE 6. **Waiting Time for MED vs Queue Time of SCS. (a) Waiting Time for MED vs Queue Time of SCS with the (LEVEL 1) of Energy recharging. (b) Waiting Time for MED vs Queue Time of SCS with the (LEVEL 2) of Energy recharging. (c) Waiting Time for MED vs Queue Time of SCS with the (LEVEL 3) of Energy recharging.**

of anxious drivers increases (i.e. above 80 anxious drivers for Level 3 energy recharging). This leads anxious drivers to choose the SCS and when its queue time increases, this situation reverses again.

Comparing the waiting time results for the 3 Levels of energy recharging, we can see that when the MED takes part more in EVs recharging (see Fig. 6c), the waiting time or queue time is not increased with such a steep mode as that of Fig. (6a, 6b). Moreover, the more interchanges between waiting time for MED or queue time for SCS in Fig. 6c and the more usage of MED for EVs charging needs at the Level 3 (see Fig. 7) fully justify the wide difference between the two charging systems (SCS), (SCS +1 MED) in Fig. 5f. So the more balanced usage of (SCS), (SCS +1 MED) charging systems, when the recharging needs of EVs are increased, approves that a combined charging system such as (SCS +1 MED) is essential.

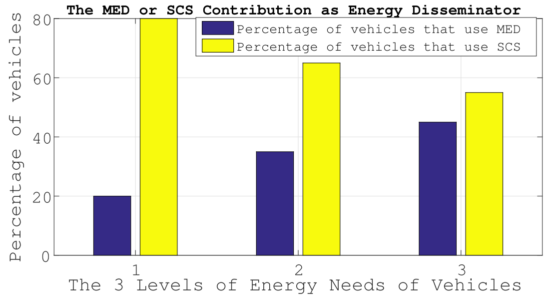


FIGURE 7. **The number of EVs that select either the MED or the SCS for their recharging needs for all the levels of Energy recharging.**

F. COST BENEFIT ANALYSIS

There are several revenue possibilities stemming from this concept as well. Electric utilities, for example, might consider subsidizing the modification of trucks and buses into MEDs under a scenario in which the utility then becomes a revenue sharing partner with the MED owner. Governments at the state, local and national levels are all involved in policy-making decisions regarding environmental impact mitigation options, often using analytical tools [41]. In this case, governments may consider offering tax incentives to modify trucks and buses into MEDs to further promote popularity and adoption of EVs.

In addition there are entrepreneurial advantages. Special software will need to be designed and refined for the physical platooning of the MEDs and EVs as well as for handling the appointment and billing logistics. Manufacturers will be asked to design and build the magnetic subsystems that create the foundation of the wireless charging systems. Converting a bus or truck into a MED would cost around 26, 000, while the cost of adding the technology to a passenger vehicle would be about 1, 500.

VI. CONCLUSIONS

We have proposed a solution for increasing the driving range of electric vehicles based on modern communications between vehicles and state of the art technologies on energy transfer. The proposed solution steers away from larger and more powerful batteries, although these would still be useful and complements what we are proposing here. It does not require changes to existing road infrastructure which are costly and often pose health hazards. In contrast to vehicle-to-vehicle (V2V) charging schemes that are recently discussed in the literature [24], our work builds on the idea of using the city buses that follow predefined scheduled routes for dynamic charging in urban environments.

Combining modern communications between vehicles and state of the art technologies on energy transfer, we have shown that vehicles can extend their travel range. Energy exchange between vehicles can be facilitated by a process called "Inductive power transfer" (IPT). This allows for an efficient and real-time energy exchange where vehicles can play an active role in the process.

Making use of inductive charging MEDs that act as mobile charging stations can improve the overall travel time of a fleet of vehicles compared to using only static charging stations. Specifically, using a MED in support of a SCS the overall travel time can be improved about four times compared with the only SCS usage case. The improvement of travel time comes with a negligible cost in travel distance, but starving vehicles otherwise would have to stop for a relatively long time or make longer re-routes to find a stationary station and recharge their batteries.

Summarizing, the main findings of the article are:

1) The concept of MEDs (Mobile Energy Disseminators) is introduced and the performance of such a system is evaluated. MEDs are ordinary buses of a city that follow predefined scheduled routes, play the role of a new kind of dynamic charging stations in urban environments without requiring changes to existing road infrastructure which are quite costly.
2) Routing of vehicles is conducted on the basis of optimizing their total travel time, with the use of an intelligent routing algorithm and through the use of wireless communication between vehicles (V2V). This routing procedure takes into account the waiting time for a MED or the queue time in a SCS and overall traffic conditions of the city with main objective the minimization of the travel time for every EV.
3) The combination of a static charging station (SCS) with a MED improves the overall travel time about four times compared to the simple SCS usage case. The waiting time and the charging time of every EV are also improved.
4) The improvement of travel time and driving range of electric vehicles comes with a negligible cost in travel distance.

As part of our future work, we intend to evaluate our proposed dynamic charging method using different evaluation parameters. Specifically, we plan to use a larger number of MEDs in combination with existing SCSs and place them in different areas of the city in order to further evaluate our dynamic charging system. We also intend to combine the proposed dynamic wireless charging with a battery swapping system, either for the MED buses or for the EVs, along with a dynamic inventory of fully charged batteries (FBs) for recharging electric vehicles depleted batteries (DBs) with the minimum charging cost [42] too.

Moreover, in our future plans is the inclusion of the dynamic electric vehicle charging (DEVC) technology of Qualcom along with SCS and MEDs. DEVC technology allows vehicles to charge while driving. For example, for only a small part of the city road network ground-based pad can be installed in order to allow the technology that uses resonant magnetic induction to transfer energy wirelessly to a pad integrated in the vehicle. That way a more dynamic charging system will be designed taking into account the additional infrastructure cost.

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DIMITRIOS KOSMANOS received the M.Sc. degree from the University of Thessaly, Greece, where he is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering. Before his current position, he was collaborating as a Fellow Researcher with the CERTH Department of Volos. He was interested in optimized video transmission techniques in wireless cooperative networks. His current research interests include techniques about improving the quality of wireless communication in vehicular ad hoc networks (Vanets)and the improved detection and suppressing jamming threats in 802.11p WI-FI protocol for Vanets and specifically for autonomous vehicles.

LEANDROS A. MAGLARAS (SM'15) received the B.Sc. (M.Sc. equivalent) degree in electrical and computer engineering from the Aristotle University of Thessaloniki, Greece, in 1998, the M.Sc. degree in industrial production and management, and the M.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Thessaly, in 2004, 2008, and 2014, respectively, and the Ph.D. degree in intrusion detection in SCADA systems from the University of Huddersfield in 2018. He is currently a part-time Senior Lecturer with the School of Computer Science and Informatics, De Montfort University, conducting research in the Cyber Security Centre. He served on the Editorial Board of several International peer-reviewed journals, such as the IEEE ACCESS and the *Journal on Security and Communication Networks* (Wiley).

MICHALIS MAVROVOUNIOTIS received the B.Sc. degree in computer science from the University of Leicester, Leicester, U.K., in 2008, the M.Sc. degree in natural computation from the University of Birmingham, Birmingham, U.K., in 2009, and the Ph.D. degree in computer science from the University of Leicester in 2013. He is currently with the KIOS Research and Innovation Center of Excellence, University of Cyprus, Cyprus. His research interests include evolutionary computation, swarm intelligence, memetic computing, combinatorial optimization problems, heuristics and metaheuristics, artificial neural networks, computational intelligence in dynamic and uncertain environments, and relevant real-world applications. He is the Vice-Chair of the Task Force on Evolutionary Computation in Dynamic and Uncertain Environments, under the Evolutionary Computation Technical Committee of the IEEE Computational Intelligence Society.

SOTIRIS MOSCHOYIANNIS received the B.Sc. degree in mathematics from the University of Patras, Greece, the M.Sc. degree in information systems, and the Ph.D. degree in theoretical computer science from the University of Surrey, U.K. He is currently a Senior Lecturer in complex systems with the University of Surrey, an Associate Member of the Surrey Centre for Cyber Security, a GCHQ—recognized U.K. Academic Centre of Excellence in Cyber Security Research, and a member of the Nature-Inspired Computer Engineering Research Group. He has published over 40 peer-reviewed publications, including three book chapters. His research interests are in the modeling and analysis of complex systems and his work on interpretable AI and machine learning as applied to path-dependency analysis is relevant to the work presented in this paper. He has been involved in a number of research projects and has received funding from the EU, U.K. research councils, government departments, and industry. He received five best paper awards at international journals and conferences.

ANTONIOS ARGYRIOU received the Diploma degree in electrical and computer engineering from the Democritus University of Thrace, Xanthi, Greece, in 2001, and the M.S. and Ph.D. degrees in electrical and computer engineering (as a Fulbright Scholar) from the Georgia Institute of Technology, Atlanta, GA, USA, in 2003 and 2005, respectively. From 2004 to 2005, he was a Senior Engineer with Soft Networks, Atlanta, GA, USA. From 2007 to 2010, he was a Senior Research Scientist with Philips Research, Eindhoven, The Netherlands. He is currently an Assistant Professor with the Department of Electrical and Computer Engineering, University of Thessaly, Volos, Greece. His research interests include wireless communication systems and networks, and video delivery. He currently serves on the Editorial Board of the *Journal of Communications*. He has also served as the Guest Editor for the IEEE Transactions on Multimedia Special Issue on Quality-Driven Cross-Layer Design, and he was also the Lead Guest Editor of the *Journal of Communications*, Special Issue on Network Coding and Applications. He serves on TPCs of several international conferences and workshops in the area of communications, networking, and statistical signal processing.

ATHANASIOS MAGLARAS (M'06) was born in Greece in 1948. He received the Electrical and Mechanical Engineering degree, the M.Sc. degree, and the Ph.D. degree from the National Technical University of Athens, Greece, in 1971, 1985, and 2010, respectively. Since 1980, he has been a Professor with the Technological Educational Institute (T.E.I.) of Thessaly, Larissa, Greece. He was the Head of the Electrical Engineering Department, T.E.I. of Thessaly, for six years. He has been the Head of the High Voltage and CAD/CAE Laboratory, T.E.I. of Thessaly, since 1990. He has authored five books concerning high voltages, electric fields, and CAD/CAE, and over 35 papers in international scientific magazines and conferences, and meetings. The main research interests are high voltages, electromagnetic field analysis, CAD/CAE, and electric vehicles. He was a member of the Technical Chamber of Greece and the CIGRE. He was a coordinator or a partner in many European research and educational projects.

HELGE JANICKE received the Ph.D. degree in computer science in 2007. He was involved in cyber security with organizations, such as Airbus Group, QinetiQ, Ministry of Defence, and General Dynamics U.K., among others. He is currently the Director of the Cyber Technology Institute, De Montfort University (DMU). He is also the Head of the School of Computer Science and Informatics. His interests are covering formal verification techniques and their application to cyber security, SCADA and industrial control system security, and aspects of cyber warfare. He established the DMU's Airbus Group Centre of Excellence in SCADA cyber security and forensics research in 2013. He is the General Chair of the International Symposium on SCADA and Industrial Control Systems Cyber Security Research. He is the Editor-in-Chief of the *Journal of Security and Safety* (EAI) and serves on the editorial board and as a reviewer for a number of international journals.