Route Optimization of Electric Vehicles based on Dynamic Wireless Charging

Dimitrios Kosmanos, Leandros Maglaras, Senior Member, IEEE, Michalis Mavrovouniotis, Member, IEEE, Sotiris Moschoyiannis, Antonios Argyriou Senior Member, IEEE, Athanasios Maglaras, and Helge Janicke

Abstract—One of the barriers to 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 article, 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 operates 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 optimisation using a graph-based shortest path algorithm. The proposed method exploits Inter-Vehicle (IVC) 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—Dynamic Wireless Charging, Electric Vehicles, Vehicular Communications, Inductive Power Transfer, Routing, Optimisation, Constraint Solving

I. INTRODUCTION

There is 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 realising 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 re-charged. 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 WV 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 transpires there is a 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. If 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.

This drives the investigation towards integrated solutions that allow EVs to charge on the move. In [7], [8] the authors
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 HGVs, LGVs or trucks, as mobile charging stations, the so-called Mobile Energy Disseminators (MEDs) [7]. 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 Figure 1.

![Figure 1: Wireless charging of EV using spiral coils](image)

Buses (inner city) and trucks (motorways) 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 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, and more specifically a solution that draws upon constraint logic programming (CLP) and a graph-based shortest path algorithm (cf Section IV). The optimisation problem of (re)routing is considered under a range of criteria and priorities.

Extensive simulations were conducted in city conditions in order to evaluate the proposed “on the move” charging technique (cf Section VII). 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.

The remainder of the paper is organised 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 [9]). 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 [10], [11] on the road side. 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 charging 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. Authors in [10] 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 another work in [16] authors present a system that can charge vehicles through inductive coupling. 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 [17].

The disadvantages of these methods can be summarised 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 [18].
- The (energy transfer efficiency) performance of the charg-
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 [19].

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 [10], [20], [21] and, unlike other proposals [22], 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 equals 100 miles. The energy charging 3 - 8 kWh requires 20 - 50 kW charging rate from the moving charging stations (see Table I). 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 [23].

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

Table I: Miles per 10-minute charge for electric cars [24]  
* This is for a 30 amp public charging station.

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.

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 [25]. 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 [25]. 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 Figure 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 Figure 2). Vehicles that book charging places on the same MED can create clusters/platoons where the MED will play the role of the clusterhead [27].

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 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 III), 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
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 energise 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), and the queue time at SCS or waiting time (wt) at MED appointment point. 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 \( S = \{ s_0, \ldots, s_n \} \) 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 \( w_t_i \).

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 \( w_t_i \). 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 \( d_{ij} \in \mathbb{R}^+ \) and a non-negative energy needed to travel \( c_{ij} \in \mathbb{R}^+ \) when points \( i \) and \( j \) are connected otherwise \( d_{ij} = c_{ij} = \infty \). The weight matrix of the problem is defined as \( D = \{ d_{ij} \}_{n \times n} \).
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 $c^k_i$. Hence, the initial energy level is defined as $c^k_s$.

Let $x^k_{ij}$ and $y^k_{ij}$ 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 $z^k_i$ and $q^k_i$ 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 I

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

$$\min \sum_{k \in K} \left( \sum_{(i,j) \in A, i \neq j} (dt_{ij}x^k_{ij}) + \sum_{i \in S \cup S'} (ct_i + wt_i)z^k_i + \sum_{i \in M \cup M'} (wt_iq^k_i) \right)$$

s.t.

$$\sum_{j \in N} x^k_{ij} - \sum_{j \in N} x^k_{ji} = \begin{cases} 1, & \text{if } i = s^k; \\ -1, & \text{if } i = t^k; \\ 0, & \text{otherwise} \end{cases}$$

(2)

$$x^k_{ij} - y^k_{ij} \geq 0, \forall k \in K, \forall j \in N, \forall i \in N, i \neq j,$$

(3)

$$c^k_j - c^k_i - (c_{ij})x^k_{ij} + (\rho_2 d_{ij})y^k_{ij} + x^k_{ij} + Q^k (1 - x^k_{ij}), \forall k \in K, \forall j \in N, \forall i \in N, i \neq j,$$

(4)

$$c^k_i \geq 0, \forall k \in K, \forall i \in N,$$

(5)

$$c^k_i \leq Q^k, \forall k \in K, \forall i \in N,$$

(6)

$$c^k_i = Q^k z^k_i, \forall k \in K, \forall i \in S \cup S',$$

(7)

$$c^k_i \geq c_{ij}, \forall k \in K, \forall i \in N, \exists j \in S \cup S' \cup M \cup M', i \neq j,$$

(8)

$$x^k_{ij}, y^k_{ij} \in \{0,1\}, \forall k \in K, \forall i \in N, \forall j \in N, i \neq j,$$

(9)

$$z^k_i \in \{0,1\}, \forall k \in K, \forall i \in S \cup S',$$

(10)

$$q^k_i \in \{0,1\}, \forall k \in K, \forall i \in M \cup M',$$

(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 Equation 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’ 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:

$$c^k_s - \left( \sum_{(i,j) \in A} c_{ij} \right) + \rho \geq 0$$

(12)

where $c^k_s$ is the initial energy level, $c_{ij}$ the energy consumed from points $i$ to $j$ and $\rho$ 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 Equation (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 [31] to calculate the shortest route, e.g., minimize the travel time in Eq 1 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., Equation (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 Equation (12), meaning that it has sufficient energy to reach the destination. If the 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.

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 point depends on the total travel time, including waiting time, charging time and
the energy point to the next energy point. In addition, the energy level may not be sufficient to reach the selected energy point (i.e., constraint (8)). Hence, the energy points that cannot be reached according to Equation (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 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.

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

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

Algorithm 2 FindBestEnergyPoint($s^k$)

1: INPUT current point of EV $k$
2: $\text{best} \leftarrow \emptyset$ % route of a best energy point
3: $p$ % best energy point
4: for ($i \in S \cup M$) do
5: $R^k \leftarrow \text{Dijkstra}(s^k, i)$
6: if (($\text{Cost}(R^k) < \text{Cost}(\text{best})) \&\& (R^k$ is feasible))
7: $p \leftarrow i$
8: $\text{best} \leftarrow R^k$
9: end if
10: end for
11: OUTPUT $p$ % best 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 Figure 3, a bus which follows a specific route (shown in yellow in the figure) 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 same probability. The point at which the EVs are inserted in SCS or MED system is shown in Figure 3 with ($m_b, s_b$ respectively). The number of EVs that are inserted...
Ptx as a quite fairly area for our evaluation experiments. The method (MED or SCS). So, our evaluation location is assumed network and there is no other communication infrastructure.

A minimum sensitivity ($P_{th}$) of $-69\text{dBm}$ to $-85\text{dBm}$ due to attenuation that is caused by the building obstacles. The Signal-to-Interference-Ratio (SINR) threshold is below the $10\text{dB}$, which gives a transmission range of $130$ to $300$ meters, as can be seen in Table III. 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 there is no communication with a few EVs. So, a number

### Table III: Evaluation parameters

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

in the system is between 0 and 100. In addition, each EV $k$ entering the system has starting energy $e_k^i$ according to a uniform distribution with values between $1-6\text{kWh}$. The only communication paths available are via the ad-hoc network and there is no other communication infrastructure. All the above parameters were not in favour of any charging method (MED or SCS). So, our evaluation location is assumed as a quite fairly area for our evaluation experiments. The power of the antenna is $P_{tx} = 18dBm$ and the communication frequency $f$ is $5.9\text{GHz}$. In our simulations, we use a minimum sensitivity ($P_{th}$) of $-69\text{dBm}$ to $-85\text{dBm}$, which gives a transmission range of 130 to 300 meters, as can be seen in Table III. 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 the 10 dB due to attenuation that is caused by the building obstacles of the city.

#### 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 at the SCS $i$ or MED $i$ through the periodical communication with MEDs or SCS (using the CAM messages). As an example, assume that the EV $k$ is located at point $(s^k_b)$ and point $(s^k_b)$ as starting point in Figure 3. 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 Figure 3).

The value for minimization with our dynamic charging algorithm is the travel time for a vehicle between the starting point $(s^k_b)$ and the target point $(e^k_b)$. The total travel time if the vehicle chooses the SCS choice depends on the travel time between the $(s^k_b,s_b)$ points, the charging time at the SCS, the waiting time here and the travel time between the $(s_b,e^k_b)$, for which the Dijkstra’s algorithm is used again. The charging rate level of the EVs at the SCS is about $19,2\text{KW/sec}$ [32]. The waiting time at the SCS depends on the queue of the SCS and the driving time between $(s^k_b,s_b)$ points. The vehicle periodically informed by the SCS about the current queue and all the bookings that SCS already has (Queue (Waiting) time ($wt_b$)). 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: $\text{WaitingTime} = wt_b - dt(s^k_b,s_b)$.

If the vehicle chooses the MED for its re-charging needs, travel time will be adjusted to reflect the travel time between the points $(s^k_b,m_b)$, the waiting time of the vehicle at point $m_b$, the time at which the vehicle follows the MED and thus is charged (the vehicle $k$ 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 $(i,j)$ in which the vehicle $m$ follows the MED to the destination point $(e^k_b)$ with the usage of Dijkstra’s algorithm. At the starting point $(s^k_b)$, the vehicle at short intervals informed by the MED about its current position $(m_i)$ and the booked road segments that MED already has.

The electric vehicle also computes the closest point $(m_i)$ 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 the 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 $m_b$, the 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 $(m_j)$). If road segments $(m_b,m_j)$ are not booked then the waiting time will be: $wt = dt\text{MED}(m_i,m_b) - dt\text{Vehicle}(s^k,m_b)$.

If the above equation is negative then the vehicle will have to go for the next cycle of the MED: $wt = dt\text{MED}(m_i,m_b) + dt\text{MED}(m_b,m_j) - dt\text{Vehicle}(s^k,m_b)$. If any road segments between $(m_b,m_j)$ are booked then the vehicle 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.

For the charging time of the vehicle from the MED, when the vehicle 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. 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 the 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, \(F_{air}\) (\([34]\)).

\[
F_{roll} = \mu_c \times m \times g, F_{air} = \frac{1}{2} C \times p \times u^2
\]  \((13)\)

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 \(\mu_c\) 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 1.2kg/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 Equation (14).

\[
P = n \times F_{Forward} \times u = n(F_{roll} + F_{air}) \times u
\]  \((14)\)

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 Equation (15).

\[
c_{ij} = P \times T_{ij}
\]  \((15)\)

If the road segment belongs to the path of a MED, then the vehicle can increase its energy by induction. The amount of the induced energy is proportional to the total time that the EV and the MED will stay connected. This time depends on the meeting point \((m_{ij})\) between the 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, Equation (15) is rewritten:

\[
c_{ij} = P \times T_{ij} - \rho
\]  \((16)\)

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

\[
\rho = t_{cont} \times C_{ind} \times P_{ind}
\]  \((17)\)

\(C_{ind}\) 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 III. We ignore acceleration and deceleration phenomena.

C. Starting Energy vs Power Consumption levels

In our simulations, we used 3 levels of starting energy 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 re-charging energy we consider that only the 20% of EVs need re-charging in order to reach at their destination (see Figure 4a). The second level of the power needs of the EVs is that in Figure 4b. Here 60% of EVs need re-charging, increasing the complexity of the system. Last, at the third level of power need and initial energy comparison almost all the EVs need re-charging (the 95% of EVs), as can be seen in Figure 4c. 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 System using 3 scenarios (see Figure 4a,4c,4e). The first charging system contains only a static charging station, and the second charging system has a SCS and a MED. In Figures 4b,4d,4f the travel time results for the above two system are presented. The sub-figures of Figure 4b,4d,4f are corresponding to the charging needs of Figure 4a,4c,4e.

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 charging needs the travel time of the dynamic charging model (SCS+ 1 MED) is better at about 2 times than that of the charging system (SCS) (see Figure 4b), at the Level 2 the corresponding travel time of (SCS + 1 MED) is improved and is now at about 3 times better than that of the (SCS) (see Figure 4d) and last at the Level 3 of re-charging needs the travel time is at about 4 times smaller than that of the only (SCS) model.

Another observation from the results is that the travel time of the (SCS+MED) system is less than the (SCS) for all the 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 Figure 5 the waiting time (wt) of each EV at the point \((m_{ij})\) that is planned to meet and follow the MED is compared with the Queue Time for each EV at the SCS. Moreover, in Figure 6 the percentage of EVs that select the MED or the SCS for re-charging 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.
(a) (LEVEL 1): The 20% of EVs need re-charging

(b) Travel Time when the 20% of EVs need re-charging

(c) (LEVEL 2): The 60% of EVs need re-charging

(d) Travel Time when the 60% of EVs need re-charging

(e) (LEVEL 3): The 95% of EVs need re-charging

(f) Travel Time when the 95% of EVs need re-charging

Figure 4: Travel Time of all the Levels of Energy re-charging

Studying more carefully Figure 5, 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 re-charging results on the increase of the waiting time. As the simulation time increases, the waiting time for MED and SCS are both widely fluctuated. This happens because the choice of EVs (MED or SCS) for re-charging are quickly interchanged. Studying the travel time of Figures 4a, 4c, 4f, 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 Figure 5) when the number of anxious drivers increases (i.e. above 80 anxious drivers for Level 3 Energy re-charging). 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 re-charging, we can see that when the MED takes part more in EVs re-charging (see Figure 5c), the waiting time or queue time is not increased with such a steep mode as that of Figures 5a, 5b. Moreover, the more interchanges between waiting time for MED or queue time for SCS in Figure 5c and...
software will need to be designed and refined for the physical environment. It is further promoted by offering tax incentives for modifying trucks and buses to MEDs, often using analytical tools [35]. In this case, governments may play an active role in the decision-making process regarding environmental impact mitigation options, often using analytical tools [35]. In this context, 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 consideration is given to 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 [35]. In this case, governments may consider offering tax incentives to modify trucks and buses into MEDs to further promote popularity and adoption of EVs.

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 [35]. In this case, governments may consider offering tax incentives to modify trucks and buses into MEDs to further promote popularity and adoption of EVs.

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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 [19], our work builds on the idea of using the city buses that follow predefined schedules and 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 or make longer re-routes to find a stationary station and recharge their batteries.

As part of our future work, we intend to explore the evaluation of above dynamic charging method with a wide diversity of evaluation parameters. Specifically, we plan to use a bigger number of MEDs in combination with the existing SCSs and different areas of the city in order to further evaluate our dynamic charging system.

**VI. CONCLUSIONS**

We have proposed a solution to 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 [19], our work builds on the idea of using the city buses that follow predefined schedules and routes for dynamic charging in urban environments.

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