Intelligent Charging Infrastructure Design for Connected and Autonomous Electric Vehicles in Smart Cities

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***Abstract*— For an environmentally sustainable future, electric vehicle (EV) adoption rates have been growing exponentially around the world. There is a pressing need for constructing smart charging infrastructures that can successfully integrate the large influx of connected and autonomous EVs (CAEVs) into the smart grids. To fulfill the aspirations for massive deployments of autonomous mobility on demand (AMoD) services, the proposed fast and secure framework will also need to address the long charging times and long waiting times of static charging, and will need to consider dynamic wireless charging as a viable solution for the CAEVs on the move. In this paper, a three-layer hierarchical charging infrastructure design that has interoperability with existing static wired charging systems and future wireless static and dynamic charging systems for Intelligent Transportation System (ITS) is presented. Charging request and reservation message frames are proposed for one of the Internet of Things application (IoT) that can enable this system to dynamically and automatically schedule charging reservations of CAEVS over one or more charging networks of different types with the shortest possible route to the destination of an AMoD trip. The hardware independent system design can detect misalignment and speed issue errors of the connected vehicles on the wireless charging pads. It employs vehicle to infrastructure (V2I) and vehicle to grid (V2G) communications with secure fog and cloud computing for faster computation and lower latencies. Finally, the proposed dynamic wireless charging network (DWCN) recommendation tool is analyzed, and its suggestions for building the proposed DWCN enables implementers to achieve the desired charge delivery performance at the lowest cost possible. The future proof system is designed to be operational with both shared and non-shared CAEVs and their AMoD trips in smart cities.**

***Keywords*—Smart City, Internet of Things, Intelligent Transportation System, Dynamic Wireless Charging, Static Wireless Charging, Cabled Charging, Vehicle to Infrastructure, Vehicle to Grid, Connected and Autonomous Electric Vehicle, Shared Autonomous Electric Vehicle, Autonomous Mobility on Demand**

I. INTRODUCTION

Since the world urban population is predicted to increase by 2.5 billion by 2050, the transportation model is deemed environmentally unsustainable for the future [1]. Fossil fuel powered vehicles contribute to noise and air pollution, cause traffic congestion, lead to parking issues in densely populated cities, and have low utilization rates [2]. The best solution to this problem would be the convergence of three emerging key technologies: electric vehicles (EVs), autonomous vehicles (AVs), and mobility-on-demand (MoD) enabled by Internet of Things (IoT).

First, EVs can promote the generation of renewable energy and reduce the carbon foot print [3]. To address long charging times and shorter driving ranges of EVs [4], Charge Point, Siemens, BP and Shell [5], and Tesla [6] have invested in construction of charging stations with fast chargers. EV users need a large number of charging networks to alleviate their fear of range-anxiety, but the charging networks can only exist if there is a demand by a large number of EVs [7].

Wireless power transfer (WPT) is of interest, as it can alleviate concerns of wired EV charging by reducing battery cost, recharge time and weight [8]. Hence, making EVs more convenient and attractive for buyers. The most promising WPT technique with high power transmission over larger charging distances is magnetic resonance coupling due to its efficiency of 96 % at resonant frequency [9]. Three types of wireless charging exists: 1) Static wireless charging (SWC) enables charging an EV while parked, 2) Quasi-dynamic charging systems are installed in dynamic environments like bus stations, traffic lights and taxi stops to provide charge while parked and 3) Dynamic wireless charging (DWC) systems are installed on long lengths of roads to charge EVs in motion [10].

Second, autonomous EVs (AEVs) are predicted to provide a safer and higher quality of transportation [11]. Shared AEVs (SAEVs) can further reduce traffic jams, greenhouse gases and transportation costs by increasing vehicle utilization and open up parking spaces [12]. Ride-hailing services are a clear initial market for SAEVs, leading to a transformational technology known as autonomous mobility on-demand (AMoD) whereby SAEVs provide personal on-demand transportation for individuals, or small groups of commuters [13].

The development of a framework for the successful integration of large volumes of EVs into electrical power systems is a great challenge. A smart city is a movement towards using technology and strategic planning to find solutions to make improvements to the environment and overall quality of living [14]. Internet of Things (IoT) devices over the internet exchange information and communicate with everything in a smart city, and can help change the operational systems within cities like by building an intelligent transportation system (ITS) [15]. As the number of EVs increase, a smart charging infrastructure is required to avoid power allocation failures and to optimize the electricity flow across the city's smart grid. A connected vehicle (CV) is part of the IoT and the future smart city by being able to access the internet and communicate with surrounding vehicles and infrastructures using Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I) including Vehicle to Grid (V2G) communications [16]. Connected and autonomous EVs (CAEVs) [17] are the key in successfully building an

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intelligent charging infrastructure for ITS in a smart city IoT application.

The existing works [18]–[21] focus on cabled charging reservation and scheduling schemes for EVs. Recently, the focus has shifted towards wireless charging, and few papers exist on proposing a charging system for CAEVs on the move [22]–[24]. However, these systems neglect the financial and environmental costs of erecting new infrastructures and fail to take advantage of the already well-established and reliable infrastructure and standards.

In this paper, the design of a fast and secure three-layer hierarchical smart charging infrastructure for both wired and wireless charging is proposed. It can help address the charge scheduling of shared and non-shared CAEVs along with privacy and security concerns without overloading the smart grid and congesting the roads and charging networks. Additionally, the proposed charging infrastructure is designed to be future proof by maintaining compatibility with the existing wired charging infrastructure standards while being interoperable with proposed SWC and DWC systems. The paper also discusses the recommendation tool that enables building a cost-effective DWC system, and that can be simulated for performance testing before real-world implementation. Two message frames are also proposed to enable charging reservations and route calculation of AMoD trips for CAEVs.

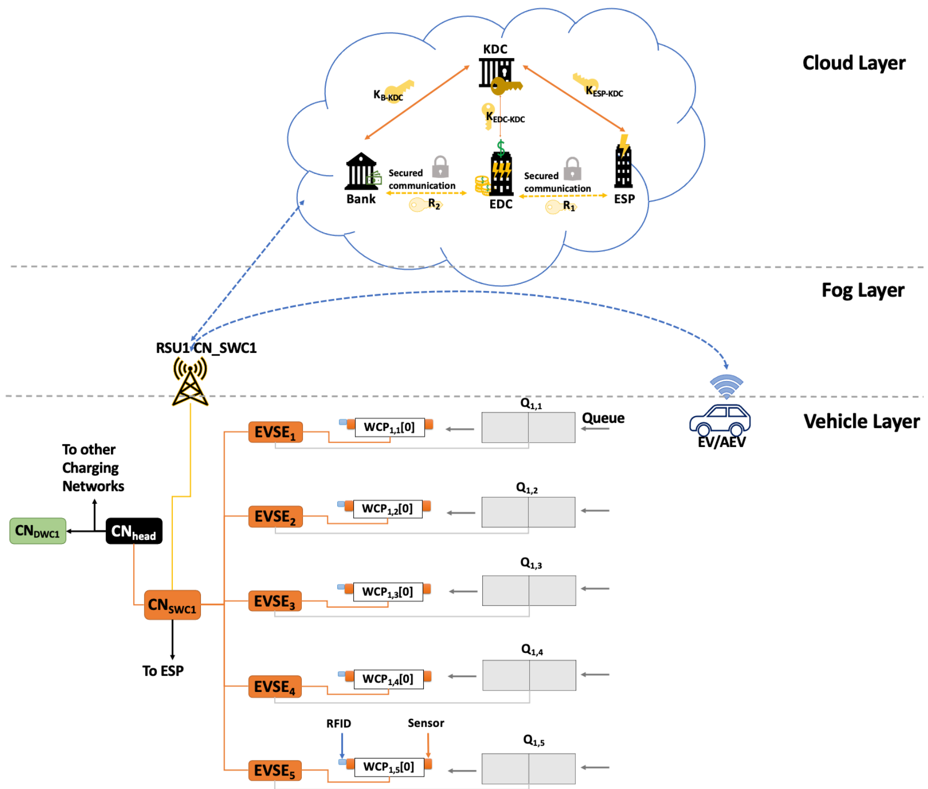

Figure 1: SWCN following the proposed three-layer hierarchical design.

Section II details the proposed charging infrastructure and accompanying message frame designs. Section III analyzes the proposed recommendation tool, and Section IV presents a discussion of our system against existing systems. Finally, Section V concludes this paper.

II. Proposed Design of a Three-Layer Hiearchial Charging Infrastructure

A. System Design

The IoT powered three-layer hierarchical system design enables static wired cable charging network (CCN), SWC network (SWCN) and DWC network (DWCN) to communicate with one another. The hierarchy of charging networks (CNs) for communication is proposed to enable fast and secure IoT service applications like fulfillment of large charging request reservations by CAEVs over multiple CNs of wired and wireless charging types. In the CN hierarchy, the CN Head (CNH) contains all information about the existing CNs, and manages and maintains the connected CNs. These CNs connected to CNH can be of two main types: 1) Dynamic charging has only one type that is DWC and 2) Static charging can have CC and SWC. This paper is focused on implementing the less prevalent wireless charging options of DWC system and SWC system to work with existing standard CC infrastructures.

The proposed CN design for SWCN and DWCN compatible with the CN hierarchy can be seen in Figure 1 and Figure 2, respectively. It can be seen that both are connected to the CNH and have the following three layers:

1) Layer 0 - Vehicle Layer:

It is composed of CAEVs and electric vehicle supply equipment (EVSE) that are wired in CCNs and wireless for DWCNs and SWCNs, and can communicate with one another using V2G. Additionally, in the DWCN, the EVSE is connected to an array of wireless charging pads (WCPs) that are embedded under a highway lane. In SWCN, the EVSE is only connected to one WCP. The SWCN and CCN EVSE’s have a queue for late and early arrival vehicles. Each WCP comes equipped with an RFID sensor, vehicle alignment and speed sensors for detecting and authenticating a CAEV and detecting misalignment and speed errors using grid to vehicle (G2V) and V2G communication.

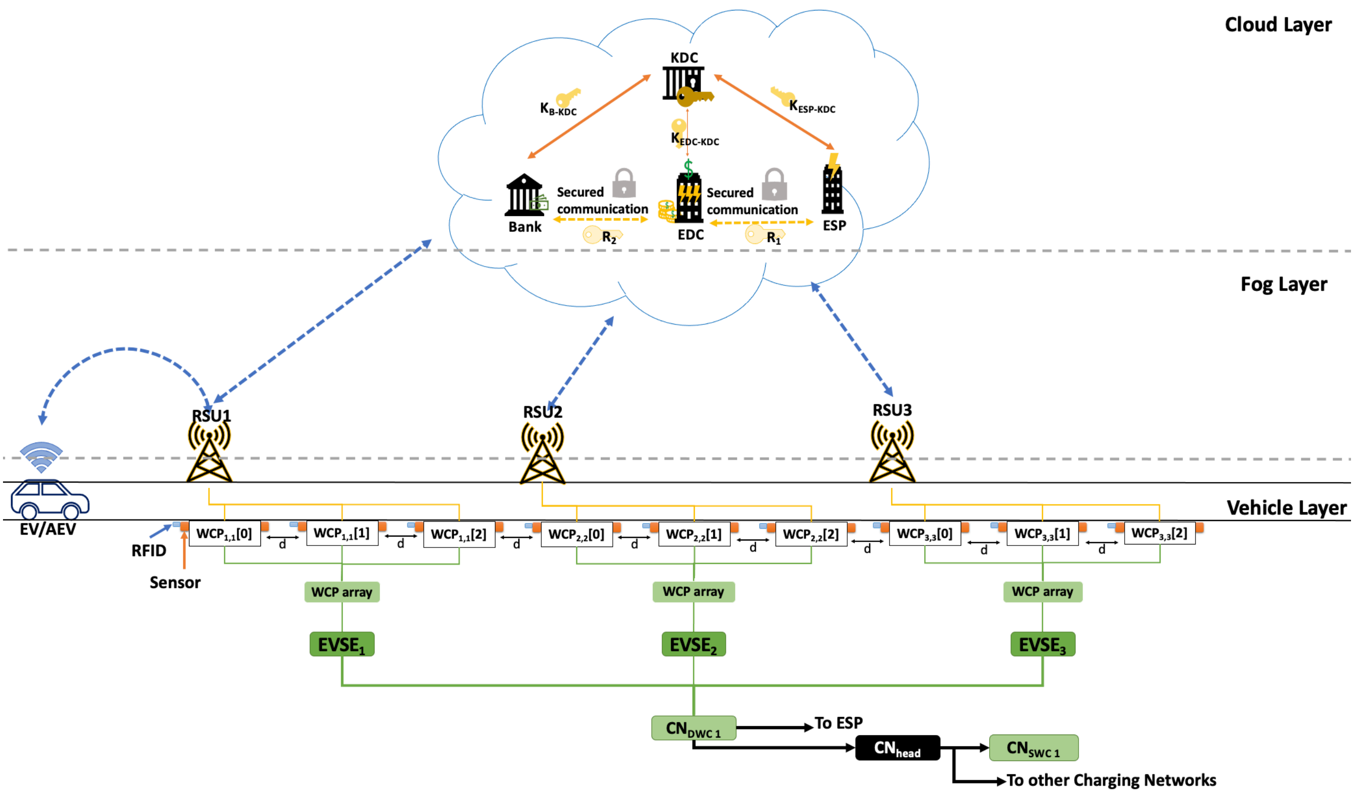

Figure 2: DWCN following the proposed three-layer hierarchical design.

Each CAEV is to be equipped with an industry standard lithium-ion battery that can be charged using both wired and wireless magnetic resonance charging systems. The on board unit (OBU) is used to record relevant information for at least a single charging session: estimated arrival time, estimated departure time, current speed, current state of charge (SoC) and requested energy.

2) Layer 1- Fog Layer:

It is composed of one or more road side units (RSUs) that act as gateways. RSUs process the incoming messages from the vehicle layer comprised of CAEVs and pass it on to the cloud layer, and communicates messages back and forth the cloud and vehicle layers. The DWCN system has one RSU for each EVSE with an array of WCPs, and has several RSUs installed along a highway lane for the moving CAEV to communicate using V2I. On the other hand, the SWCN and the CCN system have only one RSU due to their static nature. The RSUs of different CNs or the same CN can communicate with one another.

The Layer 0 CAEV uses V2I to communicate with its nearest Layer 1 RSU to request for scheduling charging reservations with the shortest possible route from its source to destination using Dijkstra's algorithm, for example. The system processes the request with help of Layer 2, and reports back the confirmation with a planned route for the trip that has stops at the static CNs with EVSE reservations and travels through DWCN's lanes. The Layer 1 RSU may also report to and from Layer 0 CAEV the vehicle speed and misalignment errors for correction in wireless charging, and may also report bills and collect real-time metered charging payments.

3) Layer 2 - Cloud Layer:

It is composed of entities that require heavy processing, power and storage, and is shared by all CNs. The cloud entities include the Key Distribution Center (KDC), Bank, Energy Service Provider (ESP) and Energy Distribution Center (EDC). The KDC enables symmetric encryption, and it is the main server which is consulted before communication can take place securely between any two entities including cloud entities, RSUs and CAEVs using a one-time session key. The CAEV users register and open a bank account in person with the Bank entity. The Bank can then act as the middle-man between the EDC and the vehicle to anonymously and securely complete Credit Points (CPs), a virtual currency, purchase and sales transactions. The CPs are encrypted to avoid forgeries. These CPs help maintain anonymity of the CAEV user and enable secure payments. Next, ESP is responsible for generating and supplying power to the CNs and its EVSEs with the help of an EDC. There can be one or more ESPs each with their own methods of generating and supplying energy. ESP is an entity that manages both the billing and the energy distribution of the energy provided by one or more ESPs. The EDC will be responsible for distributing CPs via the Bank in exchange for actual money to the CAEV user. These unique and encrypted CPs are used to pay for requested charging sessions and are sold at a fixed rate. Next, the EDC communicates with the ESPs and CNH to check the status and availability of the EVSEs for accepting or rejecting the incoming vehicle charging requests.

B. Proposed Message Frames for Charging Requests and Reservations

The messages exchanged between the Layer 0 CAEV and the Layer 1 RSU are designed to be secure and lightweight. The CAEV's OBU uses sensors and global positioning system to curate the proposed reservation request and reservation confirmation message frames that are vital for scheduling charging reservations over this system design.

The unique request ID for anonymity and vehicle privacy and security, vehicle's current speed, current SoC, requested SoC, estimated arrival and departure times and the current balance at minimum are used to build the reservation request message frame. The location ID of the RSU upon reception of the frame is added to approximately estimate the CAEV's location while maintaining location privacy of the vehicle. Then, the request message frame is sent to the Layer 3 EDC that communicates with the CNH to look for the EVSE availabilities that are closest to the contacted RSU and make as many EVSE reservations needed in one or more wired or wireless CNs. Further, the destination location can be added to the frame to help calculate the shortest possible route for the AMoD trip that traverses through the reserved CN sites.

Once reservations are confirmed, the EDC will generate a reservation confirmation frame that at minimum will contain the confirmation ID, assigned CN and reserved EVSE IDs, start and end times of reservations along with the SoC and the RSU's location ID that is reporting back to the CAEV. The confirmation ID is the same as request ID for traceability by the CNH.

III. Recommendations for Building a DWCN

The DWCN are not yet available for public use, and there are no standards available to follow for its construction and operation. Hence, a novel recommendation tool is designed to take in parameters like number of EVSEs to be installed, length of track in meters, length and width of a WCP in meters, gap in meters that need to be maintained between each WCP installation, EVSE's charging rate in kW at which the battery of a CAEV is charged, the voltage at which an EVSE operates, and the vehicle speed tolerance that can be afforded to safely supply the promised charging to a CAEV in motion. The tool at minimum then calculates and suggests the total number of WCPs that need to be purchased, required number of WCPs per EVSE, calculated length of track with WCPs installed, recommended average speed to receive charging from the track, time it will take to drive over the track in minutes and the exact locations at which each WCP should be installed on the road with gaps if any. Additional features that the recommendation tool can calculate include the length of each EVSE with WCPs installed, the time to driver over a WCP and an EVSE in minutes, energy that can be delivered by an EVSE, WCP and the track in kWh, the total number of EVSEs and WCPs needed to deliver 1 kWh of energy to a vehicle in motion, total ampere needed for EVSE's operation, the recommended maximum energy threshold in kWh for the track and its EVSE and WCPs, and the recommended time slot in minutes to use for its reservations in the charge scheduling and trip planning system proposed.

The recommendation tool is designed and tested in python version 3.9, and it is a tool that can be used both independently in recommendations for real-world construction and with a simulator that may simulate our proposed charging infrastructure design to analyze and predict performance of the DWCN in a smart city.

The tool in this paper is used alone to conduct an analysis on the effect the parameters like length of a track, length of a WCP, gap between WCPs, charge rate of an EVSE and the number of EVSEs has on the overall performance of the DWCN that is to be constructed. Equations (1) to (7) represent formulas used to calculate the total number of WCPs required for the track, the total number of WCPs required per EVSE, the calculated number of total WCPs that need to be purchased for the track, the length of an EVSE with WCPs installed, the total calculated length of the track with the WCPs installed , the time it takes to cover the length of track with the vehicle driving at the recommended speed v_{recomm} , and the total charging the track can deliver in the time it takes to travel over the track for a vehicle with the given tolerance, respectively.

$$total_{WCPs} = \frac{length\ of\ Track}{length\ of\ WCP + gap\ between\ WCP} \quad (1)$$

$$no.of\ WCPs_{EVSE} = \frac{total_{WCPs}}{no.of\ EVSEs}, where\ no.of\ EVSEs > total_{WCPs} \quad (2)$$

$$calculated_{total_{WCPs}} = no.of\ WCPs_{EVSE} * no.of\ EVSEs \quad (3)$$

$$length\ of\ EVSE = length\ of\ WCP * no.\ of\ WCPs_{EVSE} \quad (4)$$

$$calculated_{trackLen} = length\ of\ EVSE * no.of\ EVSEs \quad (5)$$

$$time_{track} = \frac{calculated_{trackLength}}{v_{recomm}} \quad (6)$$

$$charge_{track} = (time_{track} * chargeRate) \quad (7)$$

For analysis the length of the WCPs is set at 10.0 m with 2.0 m width, gap between WCPs is set at 0.5 m, speed tolerance is set at 0.5 meters per second and the charge rate of an EVSE is set at 150 kW when needed to be fixed. It should be noted that the tool following the guidelines of Ontario's government [25], [26] recommends using an average speed of 50 km/h for road lengths of 1 km to 5 km, 80 km/h for road lengths of 5 km to 10 km and 110 km/h for road lengths of 10 km and above.

First, the variable length of track is observed, and expectantly increasing the track length will increase the total number of WCPs needed to cover the track, as well as the time needed to driver over the track with the recommended average speed. Additionally, as the DWCN track length increases, the number of WCPs and EVSEs needed to deliver at least 1kWh of energy will also increase because there are more WCPs and EVSEs along the track to deliver the rest of the energy as can be seen in Figure 3.

Next, the charge rate is observed to have a profound effect on the energy delivered by an EVSE and a WCP, as increasing charge rate means that more energy can be delivered in a short time by fewer EVSEs and WCPs as can be seen in Figure 4. It is observed that increasing the number of EVSEs will mean fewer WCPs for each EVSE to cover the track as can be seen in Figure 5. However, depending on the cost per EVSE and per WCP, the implementer may decide whether having more EVSEs with fewer WCPs or more WCPs per EVSE is cost efficient for the DWCN.

Now, increasing the length of the WCP is expected to decrease the number of WCPs required to cover the track as can be seen in Figure 6, and will increase the amount of energy delivered by each WCP. Finally, increasing the gap between each WCP installation revealed that the track will be covered faster with fewer WCPs but at the cost of delivering less overall energy unless the charge rate is appropriately and safely increased to accommodate the decrease in overall charging deliverable by a track as depicted in Figure 3 and Figure 4 earlier. Further, it can be seen in Figure 7 that the longer tracks can afford more gaps between WCP installations to deliver 1kWh energy with fewer number of EVSEs and WCPs.

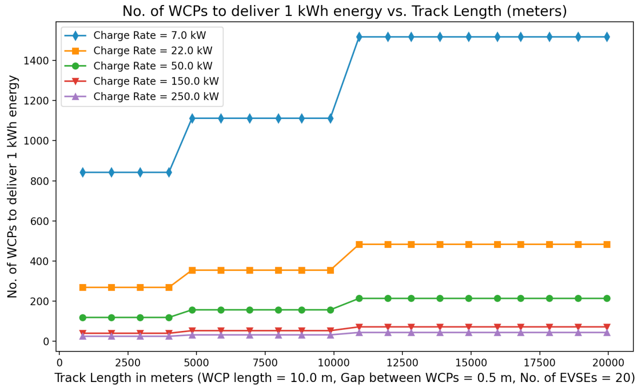

Figure 3: Track length in meters vs. No. of WCPs to deliver 1 kWh energy.

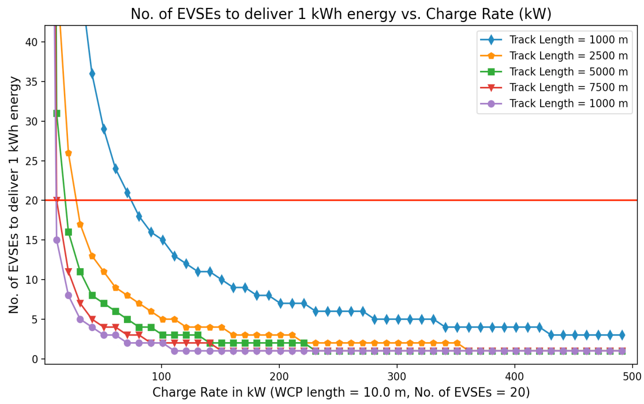

Figure 4: Charge rate in kW vs. No. of EVSEs to deliver 1 kWh energy.

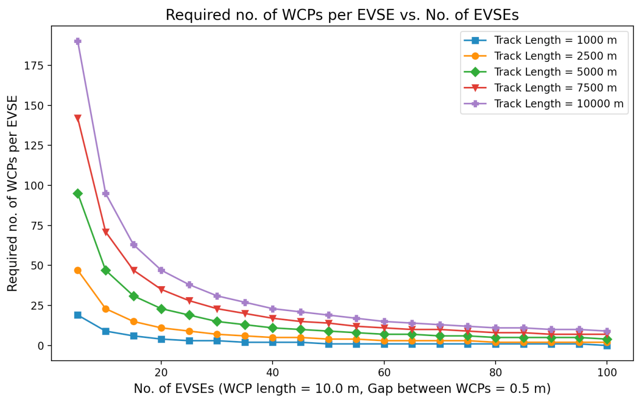

Figure 5: No. of EVSEs vs. Required no. of WCPs per EVSE.

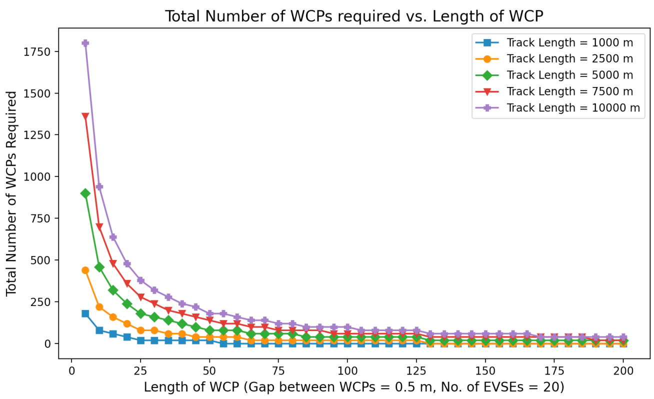

Figure 6: Length of a WCP in meters vs. Total no. of WCPs.

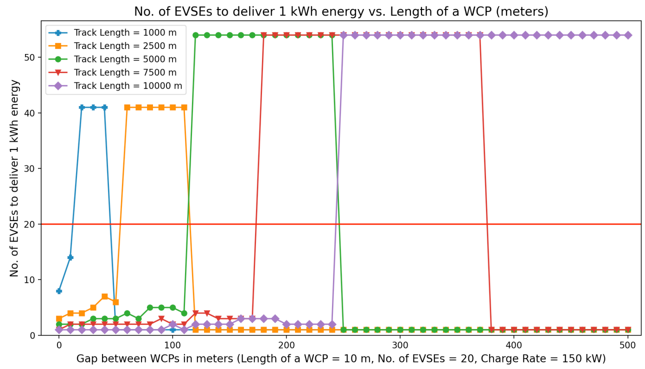

Figure 7: Gap between WCPs in meters vs. No. of EVSEs to deliver 1 kWh energy.

IV. Discussion

Planning to lay out WPT pads is a crucial task, as the layout decisions can have significant economic and environmental impacts and can reduce EV downtime. Reference [23], [27]–[29] use the inefficient WPT lanes [30], and are not compatible with existing standards. Therefore, our system with its usage of WCPs with magnetic resonance ensures interoperability with existing CCNs and future DWCNs and SWCNs. On the other hand, the system is hardware independent and can be implemented with different vehicle and misalignment detection technologies and communication technologies.

Our system like [18] solves the problem of routing vehicles for MoD applications jointly with charge scheduling to maximize EV utilization, but is not restricted to wired charging and EVs. Reference [19] optimizes both charging and routing for SAEVs to minimize waiting times and electricity costs like our system, but our system also minimizes travel time and battery consumption by finding the shortest route for the AMoD trips of CAEVs that can be both shared and non-shared. Unlike [31] that employs only V2G communication, our system also depends on V2I with fog and cloud computing for faster computation and low latency.

Our system can avoid vehicle's that steal charging by tailing vehicles also known as free-riders in DWCN like [22] by using vehicle detection sensors for authentication, and uses virtual currency to provide user anonymity and personal information privacy. The payment system is resistant to double spending with use of CPs but enables charging reservation traceability. Importantly, the system can detect misalignment and speed error issues of DWCN and SWCN and reports these errors for correction to CAEVs for efficient charging delivery. Our system contributes to the existing standardization efforts [32]–[34] that have not yet published their specifications and requirements for DWC and have considered only EVs.

V. Conclusion

The three-layer hierarchical intelligent charging infrastructure system design is made to be compatible with existing wired charging infrastructure standards while also being able to interoperate with DWCNs and SWCNs. The secure and light-weight charging reservation request and confirmation messages proposed enables this IoT application to automatically and dynamically schedule charging reservation requests of CAEVs over different types of CNs while calculating the shortest route for the AMoD trip. The recommendation tool for DWCNs enables government and private agencies to build a cost-effective DWCN with the desired performance, and it can be used in simulations to evaluate its performance in a smart city with CAEVs.

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