On the Feasibility of Vehicular Micro Clouds

Takamasa Higuchi*, Joshua Joy†§, Falko Dressler‡, Mario Gerla§ and Onur Altintas†
*Toyota InfoTechnology Center, Tokyo, Japan †Toyota InfoTechnology Center U.S.A, CA, U.S.A.
‡Paderborn University, Paderborn, Germany §University of California, Los Angeles, CA, U.S.A.

***Abstract*—This paper investigates the feasibility and the potential of vehicle cloudification, an emerging paradigm to utilize ever-growing computational resources of intelligent vehicles to form small-scale virtual cloud computing facilities. Multiple vehicles in communication range collaboratively form so-called *vehicular micro clouds*, which serve as virtual edge servers that offer data processing, data storage, communications, and sensing services not only to vehicles but also to any other types of authorized users. Although the conceptual design has been established already in the literature, the feasibility of vehicular micro clouds under practical road conditions has still to be thoroughly investigated. In this paper, we tackle this research question by analyzing vehicle probe datasets, generated by real road traffic models of the city of Luxembourg and a major intercity highway in Japan. The results indicate that connected vehicular micro clouds can be formed at many locations throughout the road networks, especially under heavy road traffic during rush hours.**

I. Introduction

A large proportion of information services for connected cars today are underpinned by interactions with remote cloud servers. To date, communications with data centers heavily rely on cellular and underlying backbone networks, which typically suffer from potentially large end-to-end latency and the capacity limits. Mobile edge computing has been considered a possible solution to overcome these issues and thereby actively developed and standardized over the recent years. The basic idea is to deploy small-scale computing facilities (*i.e.*, edge servers) near the edge of the networks, so that they can partly take over the computational tasks of cloud servers, cache the downstream data contents from the cloud, and/or aggregate upstream data traffic before sending it to the cloud. Although these help reduce the end-to-end communication latency as well as the capacity footprint in the backbone networks [1], there still remains huge data traffic in the radio access networks.

We envision that the emerging concept of *vehicle cloudification* provides a promising solution to overcome the current limitations. Imagine that we will soon have a large number of intelligent vehicles on the road, each of which has increasingly rich amount of computational resources as well as the sensing and communication capabilities. Making these vehicles collaborate with each other over vehicle-to-vehicle (V2V) networks, they could collectively form *vehicular micro clouds* that offer data processing, data storage and communication services as *virtual edge servers* (see Fig. 1). Aggregating and caching the data in the virtual edge servers, we could significantly reduce the latency and communication overhead in the cellular access networks. In addition to complementing the conventional cloud

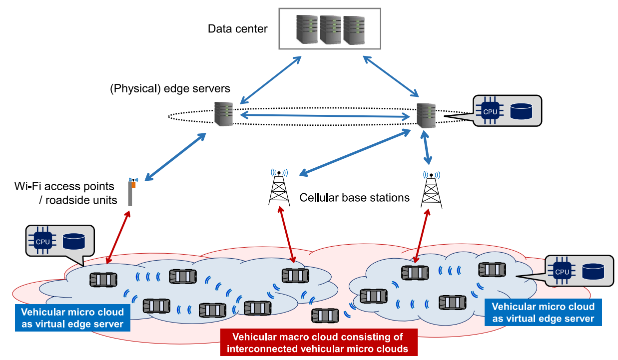


Fig. 1. Architecture of hierarchical vehicular cloud computing

and edge computing infrastructures, the vehicular micro clouds can also be an enabler of a wide range of novel applications. For instance, vehicles at an intersection can exchange their traffic congestion tables and collaboratively merge them into a more accurate table that are forwarded to other micro clouds. The micro clouds at intersections may also offer a view of traffic around the region from different angles to remote drivers requesting the service. From the content delivery perspective, the vehicles in the cloud may also take turns in downloading a popular video content from cellular networks and distribute it within the micro cloud.

Although the conceptual design has been established already in the literature [2], [3], [4], most of them evaluate their mechanisms by small-scale simulation studies, leaving the feasibility in practical environment unclear. In this paper, we tackle this research question by analyzing a realistic vehicle probe dataset from the city of Luxembourg [5] and a major intercity highway in Japan [6]. The results show that connected vehicular micro clouds can be formed at many locations throughput the road networks, allowing most vehicles to reach the nearest micro cloud in a few hops of V2V communications. We also show that these micro clouds can be interconnected over V2V links to form a wide-scale vehicular cloud network.

II. Related Work

The prior work in this domain has proposed two types of approaches for vehicle cloudification.

The first group of solutions can be categorized as *vehicular micro clouds*, where neighboring vehicles form a small-scale cluster to perform resource-intensive tasks in a collaborative manner. Gerla [2] and Lee et al. [7] established a fundamental framework for formation of a vehicular micro cloud and collaborative task execution among the cloud members. A vehicle running an application becomes a so-called *cloud leader* and recruits neighboring vehicles to join its micro cloud. The leader then splits its application task into smaller sub-tasks and distributes them to the cloud members. Once the task execution is completed, the members reply with the results, so that the leader can assemble them to obtain the final output. The resulting data content can be published and cached in the V2V network for future reuse by other vehicles. Hagenauer et al. [4] introduce the concept of utilizing vehicular micro clouds as virtual edge servers that aggregate data collected from multiple vehicles before sending them to the cloud. In addition to moving cars, some recent works investigate the possibility of integrating the resources of parked cars into the platform of vehicle cloudification [8]. The stationary nature of parked cars makes them fit well in keeping data contents in a certain geographical region, or supporting data delivery over V2V networks as virtual roadside units.

The second type of approaches is what we call *vehicular macro clouds*. All the vehicles that are reachable over V2V networks collectively form a single wide-scale vehicle cloud, spanning over the entire city [3], [9] or even multiple cities [6]. Vehicles offer their resources in the form of *services*, while a service discovery platform helps users to find appropriate service providers in the vehicular network. Mershad et al. [10] design an infrastructure-based service discovery mechanism, in which roadside units maintain a service directory that associates available services and the corresponding service providers. Car4ICT [3] enables infrastructure-less service discovery by making vehicles to collaboratively maintain the service directory over V2V networks.

While the prior works have steadily established the basis of vehicle cloudification, most of them evaluate their mechanisms by small-scale simulation studies, leaving their feasibility in practical environment unclear. One of the first attempts to address this issue is done by Hou et al. [9]. They conduct a macroscopic analysis on the amount of vehicle-provided resources in a city based on real taxi probe datasets, and successfully show the basic feasibility of vehicular *macro* clouds. In contrast, our work mainly focuses on microscopic characteristics of resource availability in a number of small geographical regions (*e.g.*, intersections), aiming to identify how stable vehicular *micro* clouds can offer services. To the best of our knowledge, we are the first to conduct such a microscopic feasibility analysis based on realistic road traffic data, which offers key insights into the potential of vehicular micro clouds as virtual edge servers.

III. Taxonomy of Vehicular Micro Clouds

Vehicular micro clouds can be further categorized into multiple types according to the following two criteria.

The first factor that characterizes vehicular micro clouds is their mobility. A *stationary* micro cloud [4], [8] is a vehicular cloud that is tied to a certain geographical region. A vehicle entering the designated region joins the stationary micro cloud, and contributes part of their resources for collaborative task execution. When exiting the region, the vehicle handovers its on-going tasks and relevant data to any other cloud member(s), so that the micro cloud can continue to provide services. This type of micro clouds usually fit well in the services generating and/or keeping data contents that are relevant to a certain geographical location (*e.g.*, local dynamic maps, etc.). In contrast, a *mobile* micro cloud is created by a vehicle running an application, as proposed in [2], [7], and move following the cloud leader. Typically, it would be suitable for the services that require long-lasting cooperation with neighboring vehicles (*e.g.*, cooperative content downloading, cooperative environmental perception, etc.).

Each type of micro clouds can be further divided into two categories depending on how they are managed. *Pre-assigned* micro clouds are managed by a control entity which plans where, when and/or under which conditions to form micro clouds. Vehicles follow instructions of the controller to form and release micro clouds. The controller can be hosted by cloud / edge servers, or even vehicular micro clouds serving as virtual edge servers. Another possible category is *on-demand* micro clouds, which are created by individual vehicles in an ad-hoc manner when they need any support by other vehicles.

Combining the both factors above results in four different types of micro clouds. Due to the limited space, we focus only on the pre-assigned stationary micro clouds and the on-demand mobile micro clouds in the following feasibility studies.

IV. Feasibility Study in Urban Area

The amount of resources that are available in a vehicular micro cloud varies over time depending on the volume of road traffic, traffic light phases, and various other factors. An ideal way to identify the feasibility of vehicular micro clouds would be to analyze real-world vehicle probe datasets. To the best of our knowledge, however, such datasets that are publicly available today usually have limited spatial and temporal granularities and/or contains only a specific type of vehicles. Thus we decided to generate synthetic vehicle probe datasets by computer simulations based on real traffic models of an urban city [5].

A. Dataset and Assumptions

To obtain the dataset for feasibility analysis, we use the SUMO traffic simulator (`www.dlr.de/ts/desktop default.aspx/tabid-9901/`), combined with the Luxembourg SUMO Traffic (LuST) scenario [5]. The LuST scenario simulates the realistic road traffic for 24 hours in the city of Luxembourg, covering an approximately 11km$\times$13km area as in Fig. 2. The road traffic is generated based on the statistical traffic demands derived from censuses, while the SUMO simulates micro behavior of individual vehicles. The number of vehicles in the simulation amounts for more than 4,500 in peak hours. We recorded locations of all these vehicles every second to obtain a vehicle probe dataset.

For simplicity of discussion, we assume that each vehicle contributes a fixed amount of virtualized resources (*e.g.*, CPU cycles, memory and data storage space, etc.) to each of micro clouds which it belongs to. Thus the total amount of

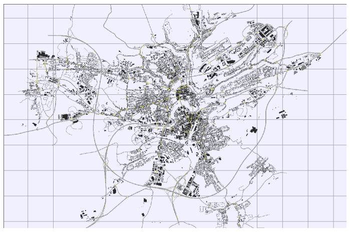
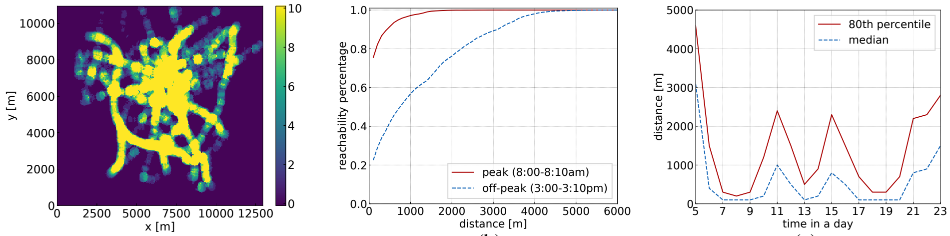


Fig. 2. Road network of the LuST Luxembourg scenario [5]



(a) (b) (c)

Fig. 3. Feasibility of stationary micro clouds in a city: (a) min. number of vehicles during 8:00-8:10am, (b) distance from every vehicle to the nearest micro cloud and (c) temporal transition of the micro cloud availability

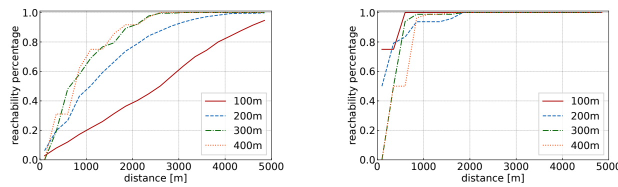
resources that are available in a micro cloud is assumed to be proportional to the number of cloud members.

B. Feasibility of Pre-Assigned Stationary Micro Clouds

We first analyzed availability of pre-assigned stationary micro clouds whose total number of cloud members never drops below a certain threshold during a designated time period for T. Such stability of resources plays a key role in many use cases of stationary micro clouds. If we want to use the micro cloud to keep and maintain a local dynamic map that covers a certain intersection, for example, the micro cloud should consistently provide a designated amount of data storage resources. Otherwise, part of the map data might be lost, or need to be backed up elsewhere (*e.g.* physical edge servers) at the cost of communication overhead.

In this particular study, we assume that a vehicle can belong to multiple micro clouds at the same time, contributing the same amount of virtualized resources to each of them. We uniformly deploy candidate locations to form micro clouds every 50m on a map, and define overlapping circular regions i, centered at these candidate points. Each region has the radius of R, where vehicles within this range can contribute their resources to the micro cloud. To estimate the performance in the worst case, we calculate the *minimum* number of vehicles $n_{i,t}$ in each region i during each time period t. Here, we set the duration T of each period to 600 seconds and the radius R to 300m (typical communication range of DSRC radios).

Fig. 3 (a) visualizes $n_{i,t}$ in each candidate region i during a time period starting from 8am. We can see that many regions consistently contain more than 10 vehicles, allowing to maintain stable stationary micro clouds. We also evaluated how easily each individual vehicle can access the virtual edge servers by V2V communications, assuming that stationary micro clouds are pre-assigned to all the regions with $n_{i,t}$ being no less than 10. Fig. 3 (b) shows the cumulative distribution of distances from individual vehicles to the nearest micro cloud. As expected, the distance tends to be longer in off-peak hours. In that case, vehicles should select whether to rely on the cloud or edge servers via the cellular networks or to continue using virtual edge servers over V2V networks in a delay-tolerant manner. The optimal selection depends on the latency and cost requirements, as well as road and network conditions. During the peak hours, in constrast, 87% of the vehicles belong to at least one stationary micro clouds, while 97% of them can



(a) (b)

Fig. 4. Feasibility of mobile micro clouds in a city: (a) distance from each vehicle to the nearest micro cloud and (b) distance among micro clouds

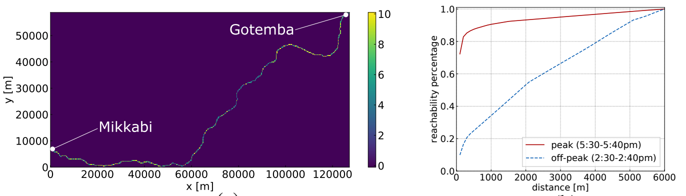
find the nearest micro cloud within 1km range (*i.e.*, typically a few hops in DSRC radios). Fig. 3 (c) shows temporal transition of median and 80th percentile distances to the nearest micro cloud. The availability of micro clouds largely varies during a day, and peaks out in the morning, afternoon and evening rush hours when they are especially needed.

C. Feasibility of On-Demand Mobile Micro Clouds

This section investigates the feasibility of on-demand mobile micro clouds in the city. In this study, we focus on a snapshot of vehicle positions at a certain point in time (*i.e.*, 8am) to evaluate if potential cloud leaders can find a sufficient number of cloud members in the vicinity. We divide the field into a set of grid cells with varying size of 100, 200, 300 and 400m, and assume that a virtual cloud leader at the center of each cell can invite other vehicles in the same cell as cloud members. Note that the reasonable spatial size of the micro clouds depends on the distance, over which cloud members can reliably communicate with the leader over V2V networks.

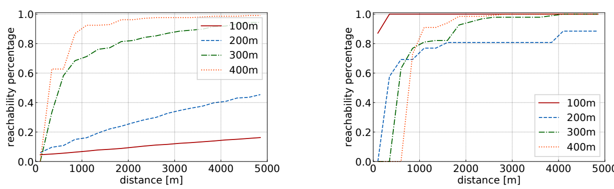
Fig. 4 (a) shows the distance of each individual vehicle to the nearest mobile micro cloud, under the assumption that a micro cloud can be formed in the cells with more than 30 vehicles. We introduce this conservative threshold to ensure, with a confidence interval of 95%, that at least two vehicles can be part of the micro cloud even if only 20% of the vehicles in the field have on-board units with the V2V communication capability. With the cloud diameter of 400m, 62% of vehicles can find the nearest mobile micro clouds within 1km range, proving the wide availability of virtual edge servers.

We also examine the feasibility of interconnecting multiple on-demand mobile micro clouds to form a wide-scale vehicular cloud network. Fig. 4 (b) shows the distribution of distances from each mobile micro cloud to the nearest another mobile micro cloud. Regardless of cloud diameters, approximately



(a) (b)

Fig. 5. Feasibility of stationary micro clouds on highway: (a) min. number of vehicles during 5:30-5:40pm and (b) distance to the nearest micro cloud



(a) (b)

Fig. 6. Feasibility of mobile micro clouds on highway: (a) distance from every vehicle to the nearest micro cloud and (b) distance among micro clouds.

90-100% of mobile micro clouds can find another mobile micro cloud within 1km range. It proves the feasibility of a vehicular *macro* cloud consisting of a number of micro clouds interconnected over V2V networks.

V. Feasibility Study on Highway

We next analyze another dataset from a highway to evaluate the impact of road types on the feasibility of micro clouds.

A. Dataset and Assumptions

In this study, we employ another SUMO simulation scenario [6] that models road traffic in the Tomei Expressway, a major intercity highway in Japan. We cover road segments spanning over 167km, and simulate vehicle mobility on the road based on the statistical traffic volume. As with the urban scenario in Section IV, we recorded positions of individual vehicles every second to generate a synthetic vehicle probe dataset.

B. Feasibility of Pre-Assigned Stationary Micro Clouds

We first analyze the feasibility of pre-assigned stationary micro clouds under the same assumptions as in Section IV-B. Fig. 5 (a) visualizes the minimum number of vehicles in each region during 5:30-5:40pm (peak), while Fig. 5 (b) shows the distribution of distances from every vehicle to the nearest stationary micro cloud during 5:30-5:40pm (peak) and 2:30-2:40pm (off-peak). Although the fast mobility of vehicles makes it challenging to form stationary micro clouds under the off-peak traffic, connected micro clouds are still available at many locations during peak hours because of the slow moving traffic around highway exits.

C. Feasibility of On-Demand Mobile Micro Clouds

We next examine the feasibility of on-demand mobile micro clouds, focusing on a snapshot of vehicle positions at 5pm. Since the vehicles on a highway typically move at high speed, it would not be reasonable to incorporate vehicles moving to opposite directions into the same mobile micro cloud. Thus we decided to analyze the east- and west-bound traffic separately, assuming that a cloud leader can invite only the vehicles moving towards the same direction. Due to the limited space, we only show the results from the east-bound traffic, while we obtained similar results from the west-bound traffic. All other assumptions are the same as in Section IV-C.

Fig. 6 (a) shows the distribution of distances from every vehicle to the nearest mobile micro cloud. The reachability to micro clouds tends to be lower than the urban case because of relatively less vehicle density on highways. However, it also shows that 87% of vehicles can find the nearest micro cloud within 1km range by setting the cloud diameters to 400m.

Finally, we examine the feasibility of interconnecting the on-demand mobile micro clouds on a highway. Fig. 6 (b) shows the cumulative distribution of distances between each on-demand mobile micro cloud. Similar to the results from the urban scenario in Section IV-C, more than 70% of the mobile micro clouds can find another micro cloud within 1km range regardless of cloud diameters, indicating the potential to form an intercity vehicular *macro* cloud, connected along highways.

VI. Conclusion

In this paper, we have investigated the feasibility of vehicular micro clouds by analyzing realistic vehicle probe datasets. The results show that micro clouds can be formed throughout the road networks, implying their potential as virtual edge servers. Meanwhile, the results in Sections IV and V also indicate that the availability of micro clouds highly depend on road traffic conditions. The optimal management of tasks, data and resources across data centers, edge servers and vehicular micro clouds thereby constitutes a key open challenge. Analysis of security and privacy concerns would be also an important step towards practical deployment.

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