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Persistence of Vehicular-Augmented Mobile Edges

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Abstract—Mobile edge computing (MEC) allows for the execution of delay-sensitive and context-aware applications close to the end-users while alleviating backhaul utilization and computation at the core network. A recent trend is to extend the capabilities of the MEC using the available resources of end-user devices beyond the edge, such as vehicles. Because of the highly mobile nature of such devices, the beyond-the-edge computing resources available at the time the MEC offloads a task decays over time. In this paper, we propose and investigate the *persistence* of groups of computational nodes in a vehicular-augmented MEC scenario. The groups are formed according to the time of arrival of vehicles and their co-location within a cell. Through the analyses of two real-world vehicular scenarios in the cities of Rome and Rio de Janeiro. On the one hand, our results show that the persistence is highly heterogeneous, depending on the vehicular traffic density and the time of day. On the other hand, we are able to identify periods during which the persistence is short and periods that show stronger stability – it becomes then possible to schedule tasks to specific time slots depending on the requirements and the expected persistence.

Index Terms—Beyond edge computing, mobility, persistence, vehicular networks

I. INTRODUCTION

Mobile edge computing (MEC) shifts cloud services to the radio access network to bring computing capabilities closer to mobile users [1]–[3]. On the other hand, MEC offers much more limited resources and, in some situations, may not scale with the number of tasks.

One appealing idea is to extend the capacity of the MEC by leveraging the available resources at end-user devices. The particular case that we consider in this paper is the *vehicular edge computing* (VEC) [4], [5]. VEC integrates MEC with traditional vehicular networks. VEC aims to move part of the communication, computing and caching resources to vehicles. It may relieve the congestion problem of backhaul links and offer untapped resources by running tasks on behalf of the MEC. Existing literature in the field lists several proposals focusing on computation offloading [5]–[8] content caching [9], and security and privacy [10]. There is a consensus that the use of vehicles is very relevant for various cases [11]–[14].

In this paper, we investigate the computation offloading capacity that a group of vehicles in a cell can offer to the MEC. We call the size of this group as the “potential” offloading capacity of the vehicular cloud. As vehicles are highly mobile, it is fundamental to investigate the dynamics of the potential offloading capacity. When the MEC is about to assign computing tasks to vehicles, it first needs to estimate the lifetime of the population of vehicles composing the vehicular

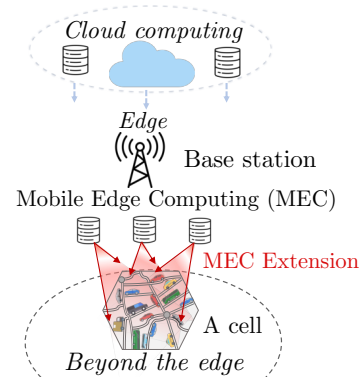


Fig. 1: Extension of the MEC beyond the edge.

cloud. In short, the question we consider is: “given the group of vehicles in a cell at time t , what is the expected duration of this group before its size decreases to a given percentage of its initial size?”. We refer to this duration as the *persistence* of the potential offloading capacity.

A straightforward way to estimate the persistence is to rely on the sojourn time of vehicles in the cell. The sojourn time is a key element in the characterization of user mobility in cellular networks [15], [16]. In the literature, only a few studies investigate the sojourn time in the vehicular context [17]. In general, vehicular mobility and traffic patterns are inferred from mobile phone connections, indicating travel patterns [17]. Other techniques, based on vehicle detectors and GPS probes, measure the residence time of cells [18]. In this study, contrary to sojourn times which characterize the behavior of vehicles on an individual basis, we look into the behavior of groups of vehicles.

We assess the persistence of the potential offloading capacity directly from groups of nodes using vehicular mobility datasets, namely in the cities of Rome and Rio de Janeiro. We introduce a reduction threshold α to characterize the point at which we assume a group has dissolved. We evaluate the persistence of groups of nodes between their formation and their dissolution – either after a short time (low persistence) or after a long time (high persistence). We point out the main differences between the datasets and their impact on the potential offloading capacity of the vehicular clouds. The main outcome of our analysis is the characterization of periods of time that should be reserved for light tasks and periods that are keen to offload tasks that require longer computation time, thanks to a more stable potential offloading capacity.

As a summary, the contributions of this paper are:

- **Persistence of a vehicular cloud.** We argue that per-

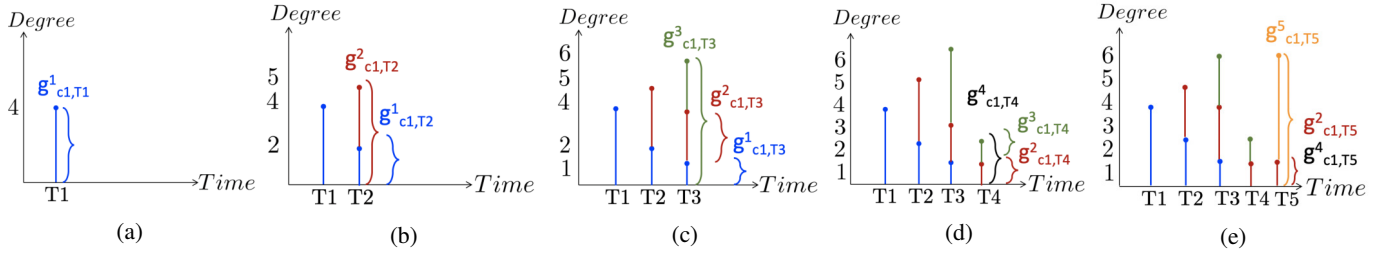


Fig. 2: Formation of groups and their evolution over time.

sistence is a crucial element for the understanding of the possibilities of using a vehicular cloud to extend the capacity of a MEC. We propose to calculate the persistence time of a cluster of resources based on their cells and their formation time.

- **Persistence time over real traffic traces.** We analyze the persistence of a vehicular cloud using two different datasets: (i) 320 taxi cabs in Rome, Italy [19], and (ii) 12,000 buses in Rio de Janeiro, Brazil [20]. These datasets are inherently different and allow us a better understanding of the possibilities that a vehicular cloud offers in terms of potential offloading.
- **Reduction threshold impact.** We introduce the notion of reduction threshold and assess its impact on the persistence of the offloading capacity. To this end, we evaluate the evolution of persistence through a combination of controlled experiments.

II. PERSISTENCE OF A VEHICULAR CLOUD

The set of vehicles in a cell represents an *offloading potential*, i.e., a measure to help us estimate the computing load that the vehicular cloud can handle. While the number of vehicles is not sufficient to determine the capacity of the vehicular cloud, it is a necessary metric to characterize the dynamics of the system. Indeed, the capacity of a vehicular cloud varies over time. By understanding such dynamics, the MEC orchestrator can have a rough idea of the way and when it should assign tasks to the vehicular cloud.

We refer to the time when the MEC offloads a task as the *offset*. We assume that vehicles receiving tasks from the MEC must remain in the cell until the completion of the task; otherwise, the task is considered lost. For this reason, we focus on the analysis of *computation offloading capacity* and of the *persistence of the vehicular cloud*, which is the time elapsed between the offset and the time the vehicular cloud dissolves.

We model a geographical area as a set of cells C . We note $g_{c,T}$ the set of vehicular nodes located in cell $c \in C$ at time T (offset). Our goal is to study the persistence of $g_{c,T}$, which is the period between T and the time at which a predefined fraction of $g_{c,T}$ leaves the cell. This fraction is specified by a variable $\alpha \in [0 \dots 1]$, which we call “reduction threshold.” The closer α approaches one, the less tolerant the offloading system is to the departures of the nodes. Therefore, the MEC can choose the right time when persistence fits best with the tasks it has to assign to vehicles.

Before giving the details about the calculation of the persistence, we formalize the reduction rate $R(t, T)$ of a group at a time $t > T$ as:

$$R(t, T) = \frac{|g_{c,t}|}{|g_{c,T}|}. \quad (1)$$

We now define a step function that characterizes the time at which the set of nodes decreases below the reduction threshold:

$$\mathbb{1}(g_{c,T}, t) = \begin{cases} 1 & \text{if } R(t, T) \geq \alpha, \\ 0 & \text{if } R(t, T) < \alpha. \end{cases} \quad (2)$$

Finally, we define the persistence as:

$$\mathcal{P}(g_{c,T}) = \int_T^{+\infty} \mathbb{1}(g_{c,T}, t) dt. \quad (3)$$

In Fig. 2, we illustrate the formation and dissolution of groups overtime for the case where $\alpha=0$ (i.e., the persistence of a group between the offset and the time when *all* nodes in the group leave the cell). At $t = T_1$ (Fig. 2a), four nodes are co-located in cell c_1 , and they form the group $g^1_{c_1,T_1}$. The persistence of this group is three-time intervals as the group vanishes at $t = T_4$. In Fig. 2b, we show the configuration of the cell one-time interval later. We notice that the cell contains, at $t = T_2$, five nodes, out of which two nodes come from the previous interval and three nodes that just joined the cell. This means that $g^1_{c_1,T_2} = 2$ and $g^2_{c_1,T_2} = 5$. The same principle applies to the remainder of the time.

It is worth noting that the persistence of $g^1_{c_1,T_1}$ is three-time intervals because of $\alpha = 0$. For example, if $\alpha = 0.5$, the persistence would have been $\mathcal{P}(g^1_{c_1,T_1}) = 2$ time intervals, because this is the time lapsed until the number of vehicles decreases to a half of the original group size.

III. DATASETS AND PERSISTENCE ASSESSMENT

In our analyses, we use two vehicular datasets composed of taxis in the city of Rome and buses in the city of Rio de Janeiro. The study of the persistence of the vehicular clouds spans a period of 24 hours. We discretize time in 5-minute intervals. We evaluate the persistence in all cells of the two cities. For the sake of clarity, we select dense and sparse areas to give a better illustration of the results. Figs. 3 and 4 pinpoint these areas in Rome and Rio, respectively. The total simulation areas are 360 km² in Rome and 1,829 km² in Rio. We divide

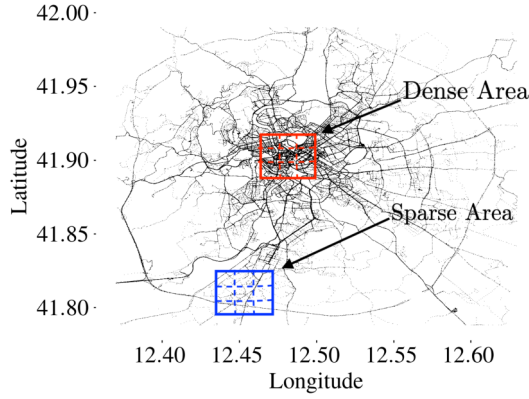


Fig. 3: Simulation area of Rome.

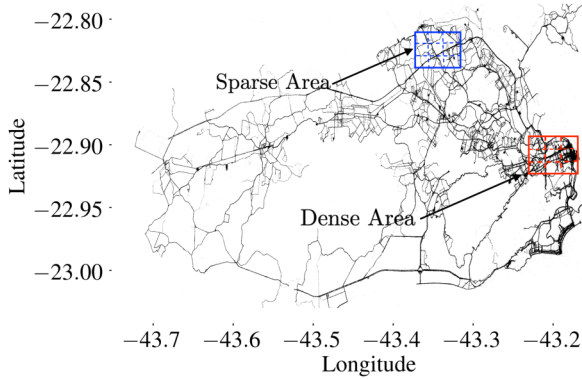


Fig. 4: Simulation area of Rio de Janeiro.

Rome’s target area into 120 cells and Rio’s into 609 cells – cells in both cases have a size of 3 km². The dense and sparse areas depicted in Figs. 3 and 4 contains nine cells each (thus, each target area in the figures covers 27 km²).

Figs. 5 and 6 show the persistence of dense cells in both cities over a period of three hours. Note that each colored curve represents the dissolution of a group over time. Recall that a group starts at each time step and that its initial size corresponds to the total number of vehicles in the cell (black dashed line in the plot).

Let us pick the specific group formed at 5:35 and describe its dynamics. In Rome, this group initially contains 11 vehicles at $T = 5:35$ am. Consider $\alpha=0$, which leads to persistence that ranges from T until all the nodes of the group leave the cell; in this case, the persistence is 2h15. Similarly, if we consider $\alpha = 0.5$, the persistence is 25 minutes, which corresponds to the period between T until half of the nodes of the group leave the cell. In Rio, this group initially contains 78 vehicles at $T = 5:35$ am. The persistence with $\alpha=0$ is 35 minutes while it is 5 minutes when $\alpha = 0.5$. Notably, the persistence in the city of Rio is lower than Rome’s despite the larger number of nodes. There is a faster decrease in the curves leading to a shorter persistence.

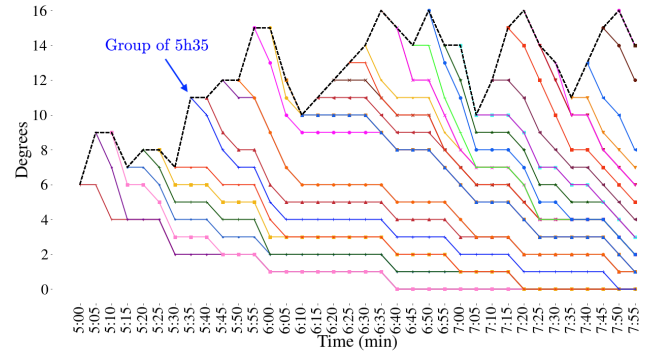


Fig. 5: Persistence of a cell between 5:00 am and 8:00 am in a dense area of Rome.

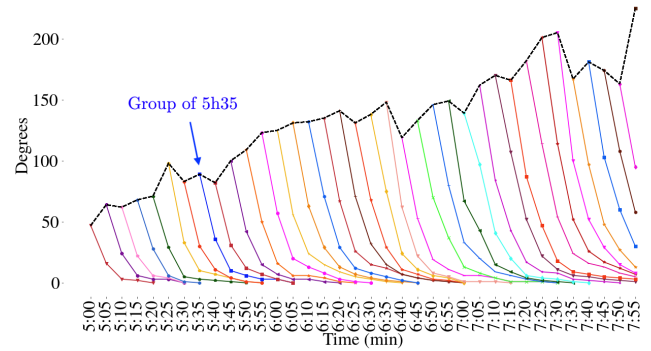


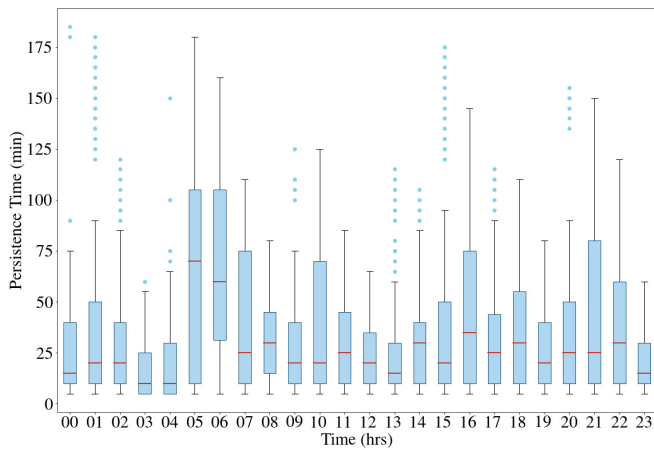
Fig. 6: Persistence of a cell between 5:00 and 8:00 am in a dense area of Rio.

IV. EVALUATION

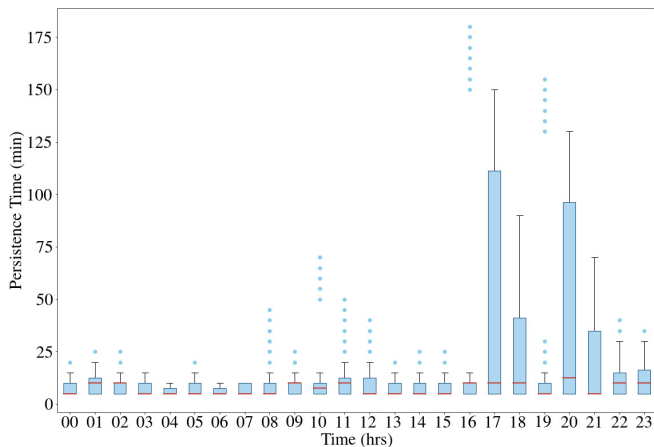
In this section, we analyze the persistence distribution in the dense and sparse areas of both datasets. To cover the full range of the dynamics (from the creation to the dissolution of the groups), we focus first on $\alpha=0$ for the plots and show results for other values of α in the form of tables. For readability reasons, we show in the plots the results on an hourly basis during a 24-hour period.

A. Persistence in Rome

Traffic density in a metropolitan area varies over the day. In the dense area of Rome, as shown in Fig. 7a, we observe the presence of extreme values (above the boxplot) with relatively high persistence. They are groups that are co-located for a long period. The shortest persistence is between 3:00 am and 4:00 am; despite the presence of extreme values, the median is the lowest. This interval is propitious to offload short computational tasks requiring low persistence (around five minutes). On the other hand, there is a persistence peak between 5:00 am and 6:00 am. The majority of the groups fall in this interval, and the median persistence is around one hour. A gradual decrease of persistence is notable until it stabilizes around 20 minutes, from 9:00 am to 12:00 pm. It indicates that the MEC could offload a task requiring high persistence in the early morning. There is an increase in the median during the intervals from 4:00 pm to 6:00 pm and from 7:00 pm to



(a) Downtown, dense area.



(b) Periphery, sparse area.

Fig. 7: Comparison of persistence between dense and sparse areas in Rome.

10:00 pm, which implies a long persistence. These intervals coincide with the peaks of activities (leaving work, school). We find, as expected, that road loads have a strong impact on persistence time.

For the sparse area (Fig. 7b), the persistence is weak for all hours except for specific intervals such as from 10:00 am to 11:00 am, from 4:00 pm to 6:00 pm, around 8:00 pm, and from 10:00 pm to 11:00 pm, due to taxis tending to move towards the periphery. The median is low between 5:00 am and 6:00 am and between 8:00 pm and 9:00 pm. The upper quartile is equivalent to a persistence between one and three hours. For these intervals, the range is extended, implying that a majority of groups have weak persistence. We could argue that it is then better to offload a computation task requiring low persistence in a sparse area.

B. Persistence in Rio

Most buses start their services between 4:00 am and 10:00 pm and operate during the whole day. We assume that extreme values in the dense area (Fig. 8a), from 12:00 am to 3:00 am, are probably due to an end of service with bus parking, and those from 4:00 am to 7:00 am by a crossover

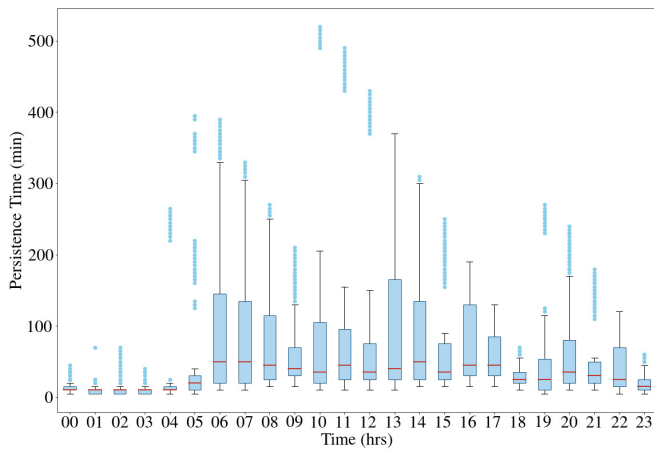
of night services and day services. Between 6:00 am and 8:00 am, we have a peak of persistence; the majority of groups are in this interval. Persistence is about 50 minutes, which facilitates the offloading tasks of this order of magnitude. During the whole day, the persistence median is around 30 to 40 minutes, suggesting us to consider that the dense area of Rio is propitious for MEC to offload tasks. Although we have an appropriate persistence, it is essential to note the presence of extreme values with a very high persistence throughout the day. The maximum persistence is 520 minutes (nine hours) at 10:00 am; these are buses with a restricted itinerary, forcing them to remain localized in a small area. In the sparse area of the city (Fig. 8b), from 12:00 am to 6:00 am, persistence is close to zero and does not exceed 10 minutes. This interval may not be appropriate to offload a task requiring long computation time, but rather for a short one. A median elevation is visible from 7:00 am to 5:00 pm, and the persistence remains relatively stable around 70 minutes. The highest median is found at 3:00 pm and the longest persistence is at noon, with the persistence of up to three hours. We observe a small increase in the median from 7:00 pm to 10:00 pm, followed by a decrease. The persistence of buses clearly depends on road traffic and especially on the route and services of the buses. Also, more buses are in service for times such as 9:00 am, 12:00 pm, and 3:00 pm. In general, the median persistence remains low with many extreme values, which means that a majority of groups have low persistence and a minority have very high persistence (up to 16 hours).

V. VARYING THE REDUCTION THRESHOLD

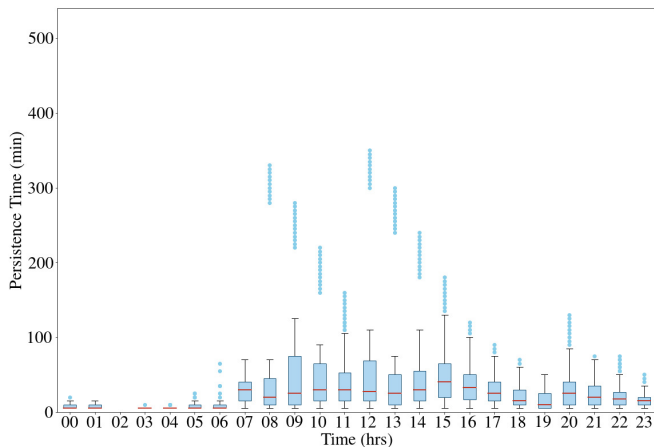
After studying the geographical distribution of persistence for $\alpha = 0$, we consider persistence with the following values of reduction threshold: $\alpha = \{0.25, 0.5, 0.75\}$. Firstly, we segment the day in 6 slots. For each time interval and dataset, we compare the dense and sparse areas. We present, in Tables I and II, the maximum persistence compared to the median for the cities of Rome and Rio, respectively. Using the median and maximum persistence allows us to study the homogeneity or disparity of it, enabling a better reflection of the dispersion. We then observe the impact of the threshold on persistence.

A. Influence of the reduction threshold in Rome

We show the impact of the reduction threshold in the city of Rome in Table I. For dense areas, the impact of the reduction threshold is visible for median persistence. For example, for the interval between 12:00 am and 4:00 am, the median persistence is equal to 15 minutes when $\alpha=0.25$, 10 minutes when $\alpha=0.50$, and five minutes when $\alpha=0.75$. Beyond a given α , the threshold no longer has an impact on the persistence. Indeed, between 12:00 am and 4:00 am, when $\alpha=0.25$, the maximum persistence time is 150. For $\alpha=0.50$ and $\alpha=0.75$, the maximum persistence time is 115. This is explained by the nodes of a given group remaining co-located for an extended period. The highest persistence falls in the interval from 5:00 am to 8:00 am. For all intervals, the extent between the maximum and median persistence is huge, so the



(a) Downtown, dense area.



(b) Periphery, sparse area.

Fig. 8: Comparison of persistence between dense and sparse areas in Rio de Janeiro.

persistence time is not homogeneous for the city of Rome in the dense area.

For the sparse area, the persistence is smaller at the periphery. Regardless of the maximum persistence and the intervals, we notice that the majority of groups have five-minute persistence. For the intervals from 5:00 pm to 9:00 pm and from 9:00 pm to 11:00 pm, there is a small variation of persistence when $\alpha=0.25$. We deduce that few groups are persistent, in the periphery, and the variation of α has no influence on the persistence time of the group. The persistence time is inhomogeneous for the city of Rome in the sparse area. We note that there is a huge maximum persistence for different α in the intervals from 1:00 pm to 4:00 pm and from 5:00 pm to 8:00 pm as long as the median remains very low.

B. Influence of the reduction threshold in Rio

The impact of the reduction threshold is less visible for the city of Rio than for Rome, as we can note when comparing Tables I and II). We observe that the maximum and median persistence are less scattered, except for the interval from 12:00 am to 4:00 am. Maximum persistence is close to the median persistence; thus, the persistence is more homogeneous

TABLE I: Reduction Threshold Variation for Rome

Rome Persistence		Dense Area		Sparse Area	
Time Intervals		Max	Med	Max	Med
[12:00 – 4:00 am]	0.25	150	15	25	5
	0.50	115	10	25	5
	0.75	115	5	25	5
[5:00 – 8:00 am]	0.25	150	25	45	5
	0.50	125	10	40	5
	0.75	125	10	40	5
[9:00 – 12:00 pm]	0.25	65	15	70	5
	0.50	50	10	55	5
	0.75	50	5	55	5
[1:00 – 4:00 pm]	0.25	120	15	175	5
	0.50	115	10	155	5
	0.75	115	5	155	5
[5:00 – 8:00 pm]	0.25	65	15	155	10
	0.50	50	10	130	5
	0.75	50	5	130	5
[9:00 – 11:00 pm]	0.25	115	15	65	10
	0.50	95	10	35	5
	0.75	95	5	35	5

for the city of Rio de Janeiro. Nevertheless, for certain intervals such as 5:00 am to 8:00 am and 1:00 pm to 4:00 pm, from a specific α ($\alpha=0.75$), the reduction threshold no longer has an impact on the median persistence. Despite a huge maximal persistence, from 12:00 am to 4:00 am, the median persistence is lowest (about 5 minutes). The dispersion of this interval is much larger compared to the median regardless of α . It means that there is a multitude of groups with low persistence; it is an off-peak time when the buses are certainly mostly inactive. Whereas from 9:00 am to 12:00 pm, persistence time is more uniform across all groups. Because of its uniformity, this interval is more suitable to receive calculation tasks for the whole group (around 10 minutes). The whole median in dense and sparse areas are around 5-10 minutes, which means we can offload a short task no matter the chosen interval and area. Table II confirms the faster decrease curves seen in Fig. 6.

Sometimes, α does not have a significant impact due either to the co-location time being too short or to the nodes staying too long. We observe that, overall, α has more impact on the persistence in a dense area.

C. Persistence in Rome vs. persistence in Rio

Proportionally, there are more buses in Rio (12,000) than taxis in Rome (320); we tend to expect a much longer persistence in Rio due to the more significant resources. We average the medians of all the intervals in the dense areas of Rome and Rio, with $\alpha=0.25$. We obtain an average persistence of 16.6 for the whole $\alpha=0.25$ of the dense zone of Rome and 9.1 minutes for the dense area of Rio. We confirm again that, despite a large number of buses in Rio, the persistence seems to be lower than in Rome. Nevertheless, the behavior is different for the sparse areas of the two cities. We obtain, by averaging all intervals medians with $\alpha=0.25$, 6.1 minutes for the sparse area of Rome and respectively 8.3 minutes in Rio. We notice the persistence is higher for the sparse area in Rio than in Rome, probably because of the type of vehicle of the two datasets. Indeed, taxis operate at the customer's request,

TABLE II: Reduction Threshold Variation for Rio

Rio Persistence Time Intervals		Dense Area		Sparse Area	
		Max	Med	Max	Med
[12:00 – 4:00 am]	0.25	265	5	20	5
	0.50	255	5	20	5
	0.75	255	5	20	5
[5:00 – 8:00 am]	0.25	15	10	40	5
	0.50	10	5	15	5
	0.75	10	5	10	5
[9:00 – 12:00 pm]	0.25	20	10	30	10
	0.50	15	10	30	10
	0.75	10	5	10	5
[1:00 – 4:00 pm]	0.25	20	10	75	10
	0.50	10	5	15	5
	0.75	10	5	10	5
[5:00 – 8:00 pm]	0.25	20	10	30	10
	0.50	15	5	20	5
	0.75	10	5	10	5
[9:00 – 11:00 pm]	0.25	20	10	20	10
	0.50	10	5	10	5
	0.75	5	5	10	5

thus have no fixed itinerary. Therefore a taxi can go from one end of the city to the other several times a day. Their mobility is not scheduled while the buses follow a defined path; the same bus line is not supposed to cross each other. Therefore, we explain a higher persistence in Rome than in Rio, for the dense area where taxis meet more often. On the other hand, in the sparse area, the taxis are concentrated in the downtown area to have more customers, while buses independently of the users make their trips in both sparse and dense areas.

VI. CONCLUSION AND PERSPECTIVES

We have explored temporal characteristics of extending MEC capabilities beyond the edge using vehicular clouds. Our work focuses on the formation of available computing groups and their spatial and temporal persistence. Our results show that the persistence of the groups follows a pattern depending on vehicular traffic density and the time of day. Analysis of the evolution of persistence suggests that peri-urban areas, which are transit zones, are well suited to short discharges (low persistence) while urban areas can handle longer tasks. Although the data analyzed are scenario-specific, we suggest dissociating high and low affluence regions to have more accurate mapping. In our future work, we will support the idea of investigating the persistence in more cities, different cells size, over longer periods, and with the same type of vehicles to improve the analysis of the evolution of persistence.

REFERENCES

- [1] J. Zhang, W. Xia, F. Yan, and L. Shen, "Joint computation offloading and resource allocation optimization in heterogeneous networks with mobile edge computing," *IEEE Access*, vol. 6, pp. 19 324–19 337, 2018.
- [2] N. Abbas, Y. Zhang, A. Taherkordi, and T. Skeie, "Mobile edge computing: A survey," *IEEE Internet of Things Journal*, vol. 5, no. 1, pp. 450–465, Feb 2018.
- [3] P. Mach and Z. Becvar, "Mobile edge computing: A survey on architecture and computation offloading," *IEEE Communications Surveys Tutorials*, vol. 19, no. 3, pp. 1628–1656, thirdquarter 2017.
- [4] L. Liu, C. Chen, Q. Pei, S. Maharjan, and Y. Zhang, "Vehicular edge computing and networking: A survey," 07 2019.

- [5] K. Zhang, Y. Mao, S. Leng, Y. He, and Y. ZHANG, "Mobile-edge computing for vehicular networks: A promising network paradigm with predictive off-loading," *IEEE Vehicular Technology Magazine*, vol. 12, no. 2, pp. 36–44, June 2017.
- [6] Q. Liu, Z. Su, and Y. Hui, "Computation offloading scheme to improve qoe in vehicular networks with mobile edge computing," in *2018 10th International Conference on Wireless Communications and Signal Processing (WCSP)*, Oct 2018, pp. 1–5.
- [7] X. Hou, Y. Li, M. Chen, D. Wu, D. Jin, and S. Chen, "Vehicular fog computing: A viewpoint of vehicles as the infrastructures," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 6, pp. 3860–3873, June 2016.
- [8] X. Chen, L. Jiao, W. Li, and X. Fu, "Efficient multi-user computation offloading for mobile-edge cloud computing," *IEEE/ACM Transactions on Networking*, vol. 24, no. 5, pp. 2795–2808, October 2016.
- [9] Y. Guo, Q. Yang, F. R. Yu, and V. C. M. Leung, "Cache-enabled adaptive video streaming over vehicular networks: A dynamic approach," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 6, pp. 5445–5459, June 2018.
- [10] J. Cui, L. Wei, J. Zhang, Y. Xu, and H. Zhong, "An efficient message-authentication scheme based on edge computing for vehicular ad hoc networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 5, pp. 1621–1632, May 2019.
- [11] K. Sasaki, N. Suzuki, S. Makido, and A. Nakao, "Vehicle control system coordinated between cloud and mobile edge computing," in *2016 55th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*, Sep. 2016, pp. 1122–1127.
- [12] J. Feng, Z. Liu, C. Wu, and Y. Ji, "Ave: Autonomous vehicular edge computing framework with aco-based scheduling," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 12, pp. 10 660–10 675, Dec 2017.
- [13] Y. C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young, "Mobile edge computing—a key technology towards 5g."
- [14] K. Zhang, Y. Mao, S. Leng, S. Maharjan, and Y. Zhang, "Optimal delay constrained offloading for vehicular edge computing networks," in *2017 IEEE International Conference on Communications (ICC)*, May 2017, pp. 1–6.
- [15] X. Lin, R. K. Ganti, P. J. Fleming, and J. G. Andrews, "Towards understanding the fundamentals of mobility in cellular networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 4, pp. 1686–1698, April 2013.
- [16] P. Baumann, W. Kleiminger, and S. Santini, "How long are you staying? predicting residence time from human mobility traces," in *Proceedings of the 19th Annual International Conference on Mobile Computing Networking*. New York, NY, USA: Association for Computing Machinery, 2013, p. 231–234.
- [17] R. A. Becker, R. Caceres, K. Hanson, J. M. Loh, S. Urbanek, A. Varshavsky, and C. Volinsky, "A tale of one city: Using cellular network data for urban planning," *IEEE Pervasive Computing*, vol. 10, no. 4, pp. 18–26, April 2011.
- [18] J. C. Herrera, D. B. Work, R. Herring, X. J. Ban, Q. Jacobson, and A. M. Bayen, "Evaluation of traffic data obtained via gps-enabled mobile phones: The mobile century field experiment," *Transportation Research Part C: Emerging Technologies*, no. 4, pp. 568 – 583, 2010.
- [19] L. Bracciale, M. Bonola, P. Loreti, G. Bianchi, R. Amici, and A. Rabuffi, "CRAWDAD dataset roma/taxi (v. 2014-07-17)," Downloaded from <https://crawdad.org/roma/taxi/20140717>, Jul. 2014.
- [20] D. Dias and L. H. M. K. Costa, "CRAWDAD dataset coppe-ufjr/riobuses (v. 2018-03-19)," Downloaded from <https://crawdad.org/coppe-ufjr/RioBuses/20180319>, Mar. 2018.