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An Edge-Assisted Data Distribution Method for Vehicular Network Services

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ABSTRACT The current data distribution method of vehicular network cannot satisfy the strict spatiotemporal constraints on the transmission of massive service data. Neither can the 5th generation mobile network (5G) meet the massive data demand of vehicular network services. To solve the problems, this paper designs an edge-assisted service data distribution method for vehicular network services. Specifically, the service data distribution was predicted by time series analysis through edge computing, based on the storage capacity of base stations. Then, a spatiotemporal constrained data sharing algorithm was proposed, which sets up a distribution tree to evaluate the importance of each vehicle in data transmission, and heuristically chooses the most important vehicles as seeds to speed up the vehicle-to-vehicle data sharing. Finally, the simulation experiment verifies that our method can greatly reduce the load of 5G network without breaking the spatiotemporal constraints of data transmission in vehicular network.

INDEX TERMS Vehicular network, data distribution, 5th generation mobile network (5G), edge computing, spatiotemporal constraint.

I. INTRODUCTION

Vehicular network integrates the Internet of Things (IoT) and mobile computing in transport, forming an open and integrated system for human, vehicle and environment. The system boasts excellent controllability, manageability, operability and credibility. To deepen the integration between human, vehicle and environment, new-generation techniques of communication and information processing are embedded in the system to help vehicles network and share information with other vehicles, human, roads as well as service platforms. In this way, vehicles can operate more intelligently and even realize autopiloting. The main communication techniques in this dynamic network include the long-term evolution (LTE) and 5th generation mobile network (5G) [1]–[4].

The typical architecture of vehicular network consists of the following layers: perception, transmission, computation and service. However, the network services are time-varying, massive in volume, highly localized and poor in real-time performance. What is worse, the transmission of service data faces strict spatiotemporal constraints. These defects are magnified with the growing service scale of vehicular network. The massive concurrent data pose a huge challenge to the capacity of air interface and backhaul network, making it impossible to meet the end-to-end delay requirements of vehicular network services with the traditional cellular networks. It is even more difficult to achieve cloud-based real-time perception of vehicle situations (e.g. location, speed and acceleration) or realize coordinated control of vehicle behaviors (e.g. network behavior and traffic behavior). Unsurprisingly, the current data distribution method of vehicular network cannot satisfy the strict spatiotemporal constraints on the transmission of massive service data [5], [6].

To solve the above problem, this paper designs a two-layer edge computing framework to coordinate the service data distribution of vehicular network based on 5G network. Under this framework, the edge server at the base station prepares the buffer strategy for the base station and the vehicle, while the edge server at the vehicle shares service data with other vehicles. On this basis, the author put forward an edge-assisted service data distribution method for vehicular network.

II. LITERATURE REVIEW

The development of vehicular network and autopiloting has brought a huge amount of data to cellular network. To cope

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with the massive data, the capacity of cellular network can be expanded through densification, but this measure will incur a high cost to the Internet service provider (ISP). Many researchers have attempted to develop a cost-effective method to alleviate the burden of distributing the massive data of vehicular network on cellular network, without scarifying the service quality.

Yang *et al.* [7] adopts the cost-effective strategy of edge caching to improve the spectrum utilization in cellular network, which solves the resource strain of air interface and backhaul network by caching popular data to the edge nodes (i.e. base stations and mobile terminals) in the mobile network [8]. Mauri *et al.* [9] precached the service data requested by vehicles to the access point on the future path, and optimized the placement of the cached data through integer linear programming. Zeydan *et al.* [10] collected user's situational information like browsing history and location, predicted user's spatiotemporal demand for service data with machine learning, and precached the popular data to base station to promote user experience. Aguayo *et al.* [11] forecasted vehicle movement with first-order Markov model, measured the forecast uncertainty by entropy, and designed an entropy-based precaching method. Fadlallah *et al.* [12] proposed an edge caching and data distribution method based on index coding. By this method, the popular data are cached randomly on mobile devices, and then distributed simultaneously by base stations to multiple users via index coding. Jiang *et al.* [13] designed an interference-aware cooperative caching mechanism among mobile devices, and studied the communication pairing for device-device data sharing. Considering the information demand of 5G users predictable, Bastug *et al.* [14] formulated a caching strategy based on the predictability, situational awareness and social network, which caches data to base station and user device at the same time.

Some researchers alleviated the bottleneck of air interface in cellular network by distributing service data with delay tolerance to other networks. For instance, Yong *et al.* [15] enhanced information dissemination through opportunistic communication, and selected the initial data source by the probability of user encounter in mobile social networks. Sun and Bin [16] proposed a heuristic algorithm that selects users from disjoint communities as the initial data sources, such that information can propagate in parallel in each community. Considering both global network and local communities, Barbera *et al.* [17] treated the central user as the initial data source, and employed various user-centered evaluation indices, such as betweenness centrality, degree centrality, closeness centrality and PageRank. Wang *et al.* [18] combined the user mobile mode of offline mobile social network with the user communication influence of online social network service, and detected the initial seed users with heuristic algorithm.

Recently, the time-constrained distribution of service data has become a research hotspot. Park *et al.* [19] predicted short-term trajectory of users based on road topology, modelled the connectivity between user devices, and then created a data distribution method based on set coverage. Li *et al.* [20] maximized load sharing under multi-linear constraints with greedy algorithm, considering the heterogeneity of mobile users and mobile data (i.e. mobile users prefer different data, and mobile data differ in volume and lifecycle). In light of the constraints of energy consumption fairness in multi-hop collaboration of mobile devices, Al-Kanj *et al.* [21] set up a comprehensive framework to optimize the distribution of data blocks, multicast transmission of mobile devices and multi-hop collaboration of mobile devices. Cherif *et al.* [22] selected potential data disseminators according to vehicle density, which improved the efficiency of data distribution. Rehmani *et al.* [23] reduce the number of data acquisition by perceiving the spatial-temporal correlation of data, thus improving the efficiency of data distribution.

The above review shows that most studies on edge caching have predicted the trajectory and service demand of users based on their behaviors, and implemented precaching in the base stations. However, there is no report that considers the group network behaviors of users, or handles vehicle network services depending heavily on locations. This calls for a data distribution method that fully satisfies the spatiotemporal constraints of vehicular network services.

III. EDGE-ASSISTED CONTENT DISTRIBUTION FRAMEWORK FOR VEHICULAR NETWORK SERVICES

In recent years, mobile edge computing has been widely adopted to enhance wireless edge capability, thanks to its ability to work under the massive data of vehicular network services.

In vehicular network, location-based services involve both service providers and vehicles V. The service providers offer vehicular network services by deploying application servers in the cloud, while the vehicles need to access service data through cellular network. To further describe the location-based vehicle network services, the set of service regions is denoted as R and the set of data blocks provided to the users as D. Note that the service regions have a one-to-one correspondence $d \dashv r$ to the data blocks. For each service region $r \in R$, there exists a data block $d \in D$ that describes the dynamic features of the region. In addition, the data blocks corresponding to r are updated at T_r intervals, and only the latest version of data is valid. Thus, vehicular network services have strict spatiotemporal constraints.

According to the principle of mobile edge computing, the computing and storage resources were deployed to wireless edges (base stations and vehicles) on two layers. At each base station, the edge server acts as a proxy or medium between the cloud server and the vehicle, and can easily obtain the situational information of the corresponding vehicle. The storage resources at each base station need to cache various types of mobile service data. Thus, the base station can reserve a limited buffer memory for vehicular network services. Meanwhile, the storage resources on each vehicle

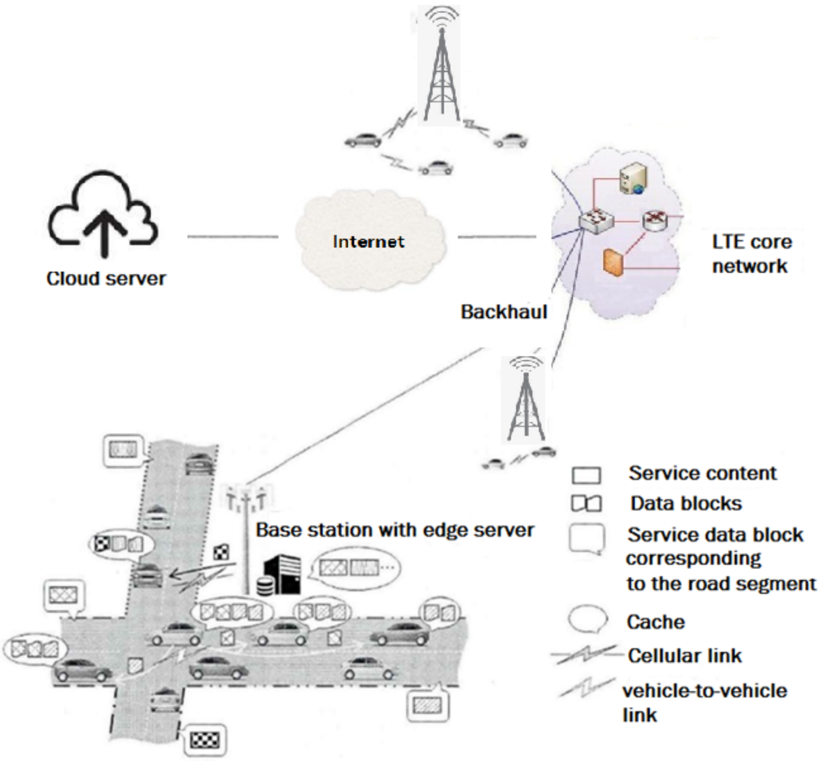

FIGURE 1. The edge-assisted service data distribution framework for vehicular network.

serve as distributed caches. The onboard caching space is linearly correlated with vehicle density. The entire edge-assisted service data distribution framework for vehicular network is illustrated in Figure 1 below.

In the two-layer (base station layer and terminal layer) edge computing framework, the edge servers schedule the service data distribution. The service requests from the vehicles are firstly processed by edge servers. If the data of the requested services are cached in base stations or vehicles, the service requests will be satisfied locally; otherwise, the service requests will be handed over to the cloud server. Since the cache performance is often constrained by the imbalance between the massive service date and the limited buffer memory of the base station, the edge servers in our framework determine the cached data of base stations in a dynamic manner. Considering the constant update of service data, the copy cached by each base station is synced with the original version of the cloud. For this reason, the edge server needs to inform the cloud server of the caching behavior. Once the cached data expire, the cloud server will push the latest copy to the edge server. To debottleneck the cellular network capacity, the edge servers only transmit the service data to a few selected vehicles rather than push the data directly to all vehicles. The selected vehicles will further disseminate the data via the ad hoc vehicular network.

In view of the location-dependent features of vehicular network services, the author put forward a spatiotemporal constrained data distribution method (Figure 2). Since the vehicles passing through the same region require the same data, the load of cellular network was reduced through data sharing without sacrificing the service quality of vehicular network.

As shown in Figure 2, the edge server of each base station schedules of data distribution, and distributes the valid data block $d(d \dashv r)$ to the vehicle in region r. The distribution can be implemented either by pushing the data block d directly to the vehicle through the cellular network, or guiding the vehicle to acquire the data block d from other vehicles via communication over the cellular network.

The key to the spatiotemporal constrained data distribution method lies in the incremental seed selection strategy. For a given region r, $S(r, t) \sqsubset S$ represents the set of seeds receiving the d from the edge server, where $d \dashv < r, t >$, it means d adheres to r, and it is valid at t time.

In the ad hoc vehicular network, the resources of opportunistic communication consumed to transfer massive data from cellular network is measured by offloading efficiency. This indicator can be described by the utility function on S, which represents maximizing load sharing efficiency:

$$U(S) = \sum\nolimits_{r \in R, v \in V} (l_d \cdot b_{v,d} - \sum\nolimits_{d' \prec d} l_{d'} \cdot b_{v,d'}) \quad (1)$$

where l_d is the size of data block d; $b_{v,d}$ represents data d which is acquired by vehicle v, $b_{v,d} = 1$ means vehicle v has acquired d through communication before entering region r. In the utility function $U(S)$, the positive and negative terms represent the total size of valid data and that of overloaded but expired data, respectively. Therefore, the objective of

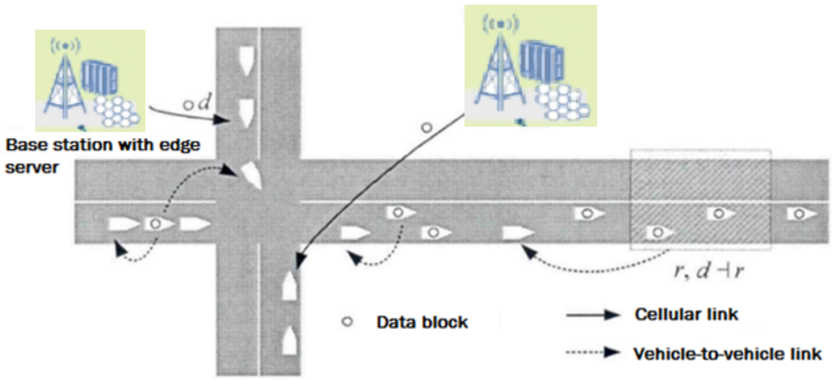

FIGURE 2. Spatiotemporal constrained data distribution method.

spatiotemporal constrained data distribution method can be summed up as maximizing the value of $U(S)$.

IV. SPATIOTEMPORAL CONSTRAINED DATA SHARING ALGORITHM

The contact/communication opportunities between vehicles are the basic elements of spatiotemporal constrained data distribution method. In this paper, these elements are described by contact graphs.

Definition 1 (Contact Graph): Let $G = (V, E)$ be a contact graph, where V is the set of nodes (users) and E is the set of edges (the contacts between two nodes). For each pair of nodes $u \in V$ and $v \in V$, the $(u, v) \in E$ is valid if and only if the two nodes have contact opportunities in the near future. Each node v has an associated set of attributes, including vehicle location, data demand, data transmission constraints and the received data blocks.

Figure 3 provides an example of contact graph. In this example, v_1 has the opportunity to meet v_2, v_3, v_4 and v_5, has received and stored d_1, and needs to acquire d_2 and d_3.

Definition 2 (Distribution Window): The distribution window is determined by the earliest start time and the latest finish time of service data distribution.

$$WIN_{v,d} = [S_{v,d}, F_{v,d}] \tag{2}$$

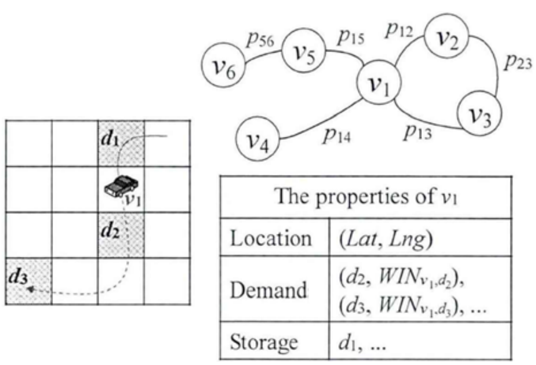

FIGURE 3. An example of contact graph.

where, $WIN_{v,d}$, $S_{v,d}$ and $F_{v,d}$ are distribution window, earliest start time and latest finish time of vehicle v to acquire data block d, respectively.

In the contact graph, each edge represents the contact probability of two vehicles in the near future. Therefore, the contact probability of each vehicle pair should be determined before plotting a contact graph.

In real-world conditions, two vehicles having moving along for a while tend to continue move along in the near future. These vehicles are often moving towards the same direction in the same road segment. This means the probability of short-term contact can be inferred from the contact situation in recent history. Since each vehicle uploads its real-time location periodically, the track of each vehicle and the contact events between each two vehicles can be obtained from the records on the edge server. A contact event occurs whenever two vehicles move within the communication region.

The contact graph G is a large graph containing all the vehicles using the same service. The nodes in the graph are connected in a complex manner. Considering the constraints of data distribution, the transmission of data blocks is limited to vehicles within the distribution window. Thus, the subgraph $G_d = (V_d, E_d)$, where $V_d \sqsubseteq V$ is the set of all vehicles requesting or possessing data block d and $E_d = \{(u, v)|u, v \in V_d, (u, v) \in E\}$ is the set of connections between these vehicles, can be derived without selecting all the seeds across the contact graph G. The seed selection can be done in parallel with each subgraph G_d.

Once selected as the seed, a vehicle $v \in V_d$ will immediately receive the data block d from the edge server via the cellular network, and will then pass d to other vehicles through the multi-hop path in the subgraph G_d. The key step in seed selection is to estimate the coverage of each potential seed. Under spatiotemporal constraints, the coverage of v to d is defined as all the vehicles that can receive valid data block d from v are considered. In our algorithm, the coverage of v to d is estimated by constructing the distribution tree $T_{v,d}$.

Definition 3 (Distribution Tree): Distribution tree $T_{v,d} = (V_{v,d}, E_{v,d})$ is a spanning tree with v as root node in subgraph G_d, where $V_{v,d} \sqsubseteq V_d$ and $E_{v,d} \sqsubseteq E_d$.

Let $p_{v \to u,d}$ be the probability that v successfully passes d to v through a given path $v \to u$ in the distribution window, where $v \to u$ is a single- or multi-hop path from v to u in G_d. Each child node u of v must satisfy $p_{v \to u,d} > \tau$, where τ is the lower bound of the probability of successful data delivery. Hence, $T_{v,d}$ is essentially a pruning tree.

The construction of a distribution tree requires the probability of data delivery. Assuming that $v \to u$ is a single-hop path, the target data block cannot be delivered from v to u unless the two nodes have at least one contact opportunity in the distribution window. Hence, the probability of data delivery can be calculated by:

$$p_{v \to u,d} = 1 - (1 - p_{uv})^{\tau_{u,d}} \tag{3}$$

where $\tau_{u,d} = (F_{u,d} - t_{curr})/ts$ is the number of remaining time windows for u to acquire d before the deadline; t_{curr} is the current time window.

For multi-hop paths, the probability of data delivery can be calculated by:

$$p_{v \to u,d} = f^{x}_{v \to u,d} \tag{4}$$

where $f^{x}_{v \to u,d}$ is the multi-hop delivery probability after removing x time windows from the remaining time windows.

The data cannot be delivered efficiently if the spanning tree is constructed by breadth-first or depth-first search. Therefore, Algorithm 1 was designed to generate the distribution tree.

Algorithm 1 Distribution Tree Construction

Input: Contact graph $G_d = (V_d, E_d)$, Node v, $v \in V_d$
Output:
Distribution tree $T_{v,d} = (V_{v,d}, E_{v,d})$ with v as root node

```
V_{v,d} ← {v}, E_{v,d} ← ∅
W ← {w | w ∈ V_d, from v to w in G_d}
while W ≠ ∅ do
    (u, v) = arg max_{u∈V_{v,d}, w∈W, (u,w)∈E_{v,d}} p_{v→u→w,d}
    if p_{v→u→w,d} > τ then
    V_{v,d} ← V_{v,d} ∪ {w}, E_{v,d} ← E_{v,d} ∪ {(u, w)}
    end if
W ← W\{w}
end while
```

Firstly, the distribution tree is initialized based on a single node v, and the candidate set W is set up to cover all nodes that will potentially be connected to the tree. Next, the most efficient edges are searched for continuously to link up the tree and the nodes of the candidate set, and the nodes corresponding to these edges are transferred from the set to the tree. This process terminates once the candidate set becomes empty.

The time complexity of Algorithm 1 is analyzed as follows. Contact graph G_d is stored in adjacency table and binary maximum heap is used to find the most efficient edges. If $|V_d| = V$ and $|E_d| = E$, the body of the while loop can execute at most V times. Let $O(\lg V)$ be the maximum time required to extract the most efficient edge from the heap. Then, the total time needed to extract the most efficient edge from the heap must be $O(V \lg V)$. Let $2E$ be the length of all adjacency tables. If it takes $O(E)$ time to update the data delivery probability of the path between the root node and candidate set, then the operation on the heap can complete within $O(\lg V)$ during the update. Therefore, the total runtime of Algorithm can be computed as $O(V \lg V + E \lg V) = O(E \lg V)$.

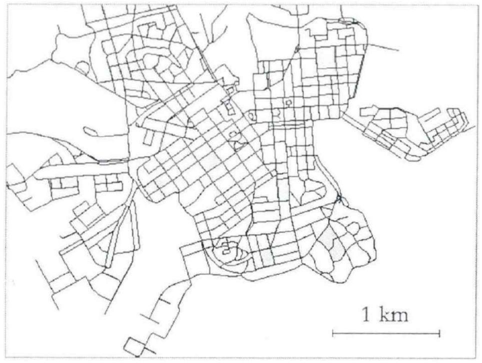

FIGURE 4. Topology of simulated roads.

The seed selection should consider different distribution windows for different vehicles. To satisfy the time constraints, the simplest strategy is to take the vehicles with early distribution deadlines as the seed of distribution. Thus, the importance of each vehicle in the contact graph should be assessed. To maximize the value of the utility function $U(S)$, the total offloading should be maximized. For each region $r \in R$, $d \dashv < r, t >$, appropriate seed allocation can be found by solving the following optimization problem:

$$\min |S(r,t)|, \quad s.t. \bigcup_{v \in S(r,t)} V_{v,d} = V_d \tag{5}$$

The above is obviously a set coverage problem with fuzzy set elements. Here, a greedy algorithm (Algorithm 2) is proposed to obtain the approximate optimal solution of the problem. The selected seed vehicles in Algorithm 2 can disseminate data in parallel in different distribution trees.

Firstly, a distribution tree is generated for each vehicle in the contact graph and the importance of each vehicle is assessed. The vehicles be selected as seeds or covered by the selected seeds are collected into the set C. Then, the most important vehicles are selected from set C as seeds. Once a seed s is selected, the vehicles covered by s are removed from the set, because they have the opportunity to directly or indirectly obtain data from s. Based on the latest subgraph $G_d[C]$, the distribution tree is updated and the importance of each remaining vehicle in C is reassessed.

V. EXPERIMENT AND RESULTS ANALYSIS

Our experiment evaluates the proposed edge-assisted service data distribution method for vehicular network with two performance indices, namely, total offloading and offloading rate.

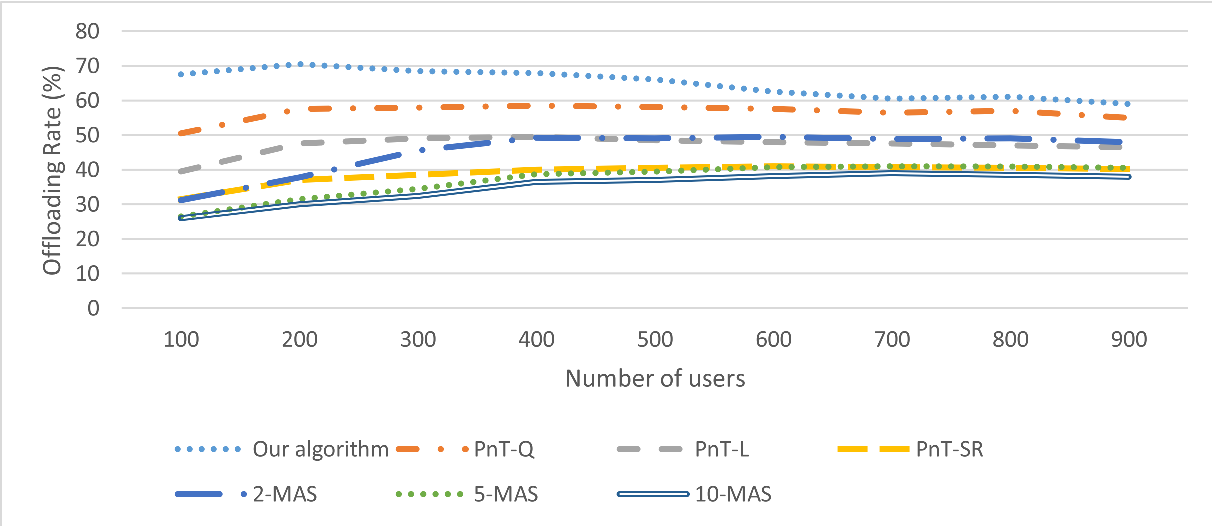

FIGURE 5. **The relationship between the offloading rate and the number of users.**

Algorithm 2 Seed Selection

Input: Contact graph $G_d = (V_d, E_d)$
Output: Seed set $S(r, t)$ selected at current time t, and $d \dashv < r, t >$
  $S(r, t) \leftarrow \emptyset$
  for each $v \in V_d$ do
    Distribution tree $T_{v,d} = (V_{v,d}, E_{v,d})$ is constructed by Algorithm 1
    $I_{v,d}$ is computed
  end for
  $\mathrm{C} \leftarrow V_d$
  while $\mathrm{C} \neq \emptyset$ do
    $s = \arg\max_{v \in C} I_{v,d}$
    $\mathrm{S}(r, t) \leftarrow S(r, t) \cup \{s\}$
    $\mathrm{C} \leftarrow \backslash \mathrm{C} V_{s,d}$
    for each $v \in C$ do
      $T_{v,d}$ is updated by subgraph $G_d[C]$
      $I_{v,d}$ is updated
    end for
  end while

The proposed method was implemented on an opportunistic network environment simulator. Corresponding to different congestion levels, the effectiveness of data decreases during transmission. All the vehicles in the simulation were installed with a 5G cellular radio interface (Full band below 6GHz and above 6GHz). The simulation area is fully covered by the cellular network, so that the edge server can communicate with the vehicle at any time. Traffic diversion capability is the key index of traffic situation awareness and traffic information dissemination scheme. The different warning levels given by the scheme vary with the change of real-time traffic situation. When the congestion level increases, more vehicles will be diverted before reaching the congested area to avoid further deterioration of traffic congestion. As shown in Figure 4, actual roads in Beijing were selected from a 4.2×3.2 km^2 area for simulation. The 2h-long experiment contains three independent simulations. The mean value of the three simulation results was taken as the final experimental result.

The proposed method was compared with the k-most anxious user (k-MAS) method and the push-and-track (PnT) method [24]. In the two contrastive methods, the edge server will directly push the data blocks to the users via the cellular network, if some users fail to receive the required data before the end of their respectively time window or the remaining time is insufficient to transmit the data via the cellular network.

To validate the edge caching strategy of base station based on predicted data popularity, the trajectory data of 50,000 plus vehicles in Beijing were recorded in 22 working days and used to simulate the vehicle service requests in the study area. The offloading rate of our method was compared with that of other methods.

The relationship between the offloading rate and the number of users was investigated as the data size ranges from 1MB to 10MB. The results are displayed in Figure 5, where FPnT-Q, PnT-L and PnT-SR are PnT methods using quadratic function, linear function and square root function as objective functions, respectively, and 2-MAS, 5-MAS and 10-MAS are k-MAS methods with different number of users.

It can be seen from Figure 5 that our method clearly outperformed the k-MAS and PnT methods, especially with a few users. The offloading rate of our algorithm could reach 70%, while that of the other methods never exceeded 60%. It can also be inferred that all methods saw the offloading rate increase rapidly before a steady decrease. The max value of offloading rate appeared in about 200 users. When there are a few users, the simulation area has a sparse distribution of vehicles. As a result, the vehicles requesting the same data are far from each other, making it difficult to transmit the data blocks via the opportunistic vehicular self-organizing network. Even in this case, our method still achieved a good performance, because it can evaluate and utilize the importance of each vehicle in opportunistic propagation. When there are many users, the vehicles requesting the same data were close to each other and have many opportunities to communicate with each other. That is why the offloading rate of all methods was on the rise in this case. Nevertheless, further increase in the number of users will make the ad hoc vehicular network crowded with vehicles, causing a steady decline in the offloading rate.

In the experiment, the size of data blocks is randomly and uniformly generated in each corresponding range. The simulation results show that the proposed algorithm has the best performance among all the schemes, especially for smaller data blocks, the advantages of the proposed algorithm are more obvious. However, with the increase of data block size, the load sharing rate of all schemes will decrease. The reason for this phenomenon is that the short contact between vehicles is difficult to complete the transmission of large data blocks. Therefore, in order to improve the efficiency of load sharing, the coordinator can divide large data blocks into several small data blocks before using the proposed algorithm.

VI. CONCLUSION

Focusing on location-based services in vehicular network, this paper proposes a two-layer edge computing framework and an edge-assisted data distribution method for vehicular network services, with the aim to enhance the ability of cellular network to satisfy the quality of service (QoS) requirements of vehicular network services. Specifically, the data communication opportunities between vehicles were described through dynamic maintenance of a probability-based contact graph, and the importance of each vehicle in seed selection was evaluated by a distribution tree derived from the contact graph. Next, the author designed a heuristic greedy algorithm to select the proper seeds for data distribution, which speeds up the data sharing between vehicles. The simulation experiment results show that our method can effectively alleviate the bottleneck of air interface and backhaul network without breaking the spatiotemporal constraints on distributing the service data of vehicular network.

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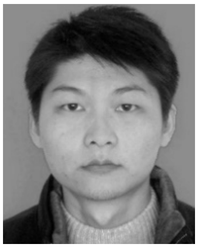

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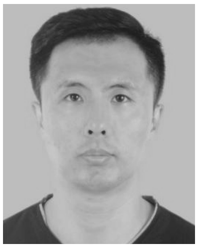

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