Integrated VLC/RF Wireless Technologies for Reliable Content Caching System in Vehicular Networks

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ABSTRACT In a vehicular communications environment, the need for information sharing, entertainment, and multimedia will increase, leading to congestion of backhaul networks. The major challenge of this network is latency and resource limitations. Proactive caching can be obtained from local caches rather than from remote servers, which can avoid long delays resulting from limited backhaul capacity and resources. Therefore, proactive caching reduces latency and improves the quality of services. Determining which files should be cached in memory is a critical issue. The paper proposes various placement schemes for caching at the vehicle and mobile base station (MBS) layers. The optimal caching place represents better user demand and latency based on the demand and mobility model. Non-cooperative and cooperative vehicles with vehicle-to-vehicle communication (V2V) are included. In both models, the high data rate of visible light communication (VLC) in the vehicular networks tends to enhance the caching capability. We also illustrate a sub-optimal algorithm to solve optimization problems compared to the optimal brute force solver and the sub-optimal genetic algorithm. Numerical results show that proactive caching schemes have a significant gain in system performance. The analysis shows that VLC improves proactive caching performance when there are less than 25 vehicles. The joint proactive caching scheme works better as the number of vehicles increases. The V2V proactive caching is useful when vehicles per platoon are ≥ 10

INDEX TERMS 6G, proactive caching, vehicular networks, visible light communication (VLC), radio frequency (RF), vehicle-to-vehicle communication (V2V), cooperative and non-cooperative vehicles.

I. INTRODUCTION

The next-next generations of cellular networks, such as 5G and beyond, are expected to affect any sector and daily operation by delivering connectivity everywhere at high speed [1], [2]. Nonetheless, highly integrated devices and rapid data transmission would pose significant privacy, latency, and energy consumption problems. The massive demand for quality of high-reliable network services have significantly changed how the network could operated.

In recent years media contents traffic from vehicles has increased rapidly. Due to a large amount of demand, proactive caching is an efficient method of reducing backhaul traffic. One of the most effective criteria in caching benefit is

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caching placement [3]. The caching technique at roadside units (RSUs) is a promising way to minimize communication latency between the edge nodes and the connected vehicles [4]. The minimum communication latency in Vehicular Ad Hoc Networks (VANETs) could be achieved by applying proactive caching on the RSU-based highway model. They used user demand and mobility to determine the most appropriate caching files. The latency of the network was taken into consideration as a performance measure. Thus, for caching schemes, optimization problems are formulated to minimize it for non-cooperative and cooperative schemes that reason about cache popularity. The greedy algorithm was able to solve the problem for each of the schemes. In [5], a city model was studied which focused on the impact of proactive caching on non-clustered and clustered cache schemes. Information on vehicle demand and mobility patterns was exploited to

develop cache file placement in vehicles before their present demand. They proposed a sub-optimal caching scheme to solve the optimization problems they encountered.

Vehicles have various capabilities to be caching nodes, such as an appropriate power source, memory, mobility, and on-board processing unit (OBU). Due to the advantages of caching in vehicles, vehicle-to-vehicle communication (V2V) is pushed to exploit [6]. To ensure long-term data storage, they developed a distributed data scheme by caching vehicles. In which the vehicles can communicate information to each other when they were both in movement. Caching in parked vehicles was also used to improve the caching hit ratio of Vehicular Content Networks (VCNs), which VANET used for streaming live video content [7]. Further- more, cache-based mobility is used between two layers; the vehicular and roadside unit layers of VANET architecture are proposed in [8]. They attempted to solve the optimal latency values, which would minimize the average latency of content retrieval. They first divided the problem into sub-problems and simultaneously solved convex optimization and stim- ulated anneal (SA) methods to optimize them. Caching in vehicles and RSU was evaluated using the vehicle demand profile and velocity in the highway network traffic model. They suggested a hierarchical proactive caching scheme to minimize the time of content retrieval by determining caching placement according to the order of the provider nodes.

The most common communications technologies are dedi- cated short-range communications (DSRC), and cellular net- work technologies [9]. The DSRC standard developed for this type of network is IEEE 802.11p. It is working at 5.9GHz using radiofrequency to communicate at a data rate that ranges between 3 and 27 Mbps and can be achieved at a range of up to 1000 meters [10]. The performance of DSRC will be degraded with the increase in the number of vehicles attempt- ing to transmit in the same channel simultaneously due to the packet delay and probability increases of transmission col- lision. Therefore, extra investment and new communication technologies should be presented to overcome a large amount of vehicle data.

Although, the investment in road construction is somewhat capable of alleviating traffic congestion to some degree. It is not sustainable because of the high cost of construction and limited resources. To overcome these problems, a more suc- cessful solution is to shift the driving pattern from individual driving pattern to platoon-based driving pattern [11]. The platoon-based driving pattern is a cooperative driving pattern for a group of vehicles equipped with common interests, in which the vehicles maintain a small and nearly distance to the preceding vehicles. The platoon-based driving pattern could significantly improve network throughput, and energy efficiency [12]. The platoon method allows for many kinds of advantages. In a platoon, vehicles are much closer to each other, allowing the capacity of the road to be increased while decreasing traffic congestion. It is also possible to reduce energy consumption and exhaust emissions by max- imizing the number and distribution of vehicles in a platoon.

Furthermore, the platoon-based driving pattern facilitates high potential cooperative communication applications in data sharing or dissemination due to the relatively fixed position for the vehicles within the same platoon with low network latency, which may improve vehicular networking performance.

Recently, there are an increase in low-cost hardware and installation of visible light communication (VLC) equipment. This advancement gives an incentive for many researchers to use VLC in vehicular networks. A low-complexity and high-reliability system of V2V communication using VLC was developed in [13]. The VLC can significantly improve the performance of V2X networks by eliminating the lim- itations of conventional RF-based V2X communications. However, since the VLC link is designed for a short commu- nication range and can be blocked by obstacles, the reliability can degrade when the vehicles move at high speeds [14]. The hybrid VLC/RF structure facilitates constructing an efficient and reliable VANET [15].

This paper develops a promising scheme that provides proactive caching of the vehicle layer and the remote light units (RLUs) layer. In the vehicular networks, data sent at a high rate is also used to minimize the overall cost of data and to ensure a high dissemination of caching data in the same network. The benefits of RLU include reducing latency and blocking while providing a high data rate of up to 100Mbps. Optimal caching positioning is designed to minimize commu- nication latency for vehicle requests based on user demand and the mobility model. Also, we study three scenarios: non-cooperative, cooperative vehicles, and the area covered by RLUs. Sub-optimal algorithms were developed in three scenarios to solve optimization problems compared to the optimal brute force solver and the sub-optimal genetic algo- rithm. Numerical results show that proactive caching schemes have a significant gain in caching. Moreover, the impact of the number of files, the density of vehicles and the platoon size are presented.

The remainder of the paper is structured as follows. Previ- ous related works are presented in Section II. In Section III, the system model and used technologies are introduced. Section IV describes the problem formulation and developed algorithm. Section V shows computational simulation results and comparative studies. Finally, a conclusion and future work are drawn in Section VI.

II. LITERATURE REVIEW

In order to obtain real-time data delivery required by vehicu- lar services and ensure efficient transmission, an in-vehicle edge computing caching scheme is developed [16], [17]. A collaboration system is presented to efficiently motivate vehicles to offload hot applications to the edge server to optimize the benefit of both vehicles and the edge server so that the edge server can share the data with other vehi- cles. A Manhattan mobility model was characterized in [5]. In order to increase the caching ability, vehicle demand and mobility patterns are used. Non-clustered and clustered RSU

caching scheme was proposed. Then, their caching schemes were compared with the baseline reactive scenario. In [18], the authors proposed a model for V2V caching strategy in a software-defined 5G-enabled VANET. As a result, a small base station (SBS) enables mobile vehicles to store common contents on their caches and supports the surrounding vehicles by providing a reward. The main objective of the SBS is to minimize content delivery latency, reduce traffic congestion, and offload cellular core links. The interaction between the SBS and the cache-enabled vehicles is formulated using a Stackelberg game with a non-cooperative sub-game to model the conflict between the cache-enabled vehicles on the limited number of common SBS files.

In [19], based on the content popularity distribution, connectivity, and current caching status, a connectivity-aware content caching algorithm was proposed to maximize total caching utilize, which was defined as caching gain and caching cost. They assumed that each content was divided into some chunks. Their algorithm determined the caching decision of received chunks at each vehicle. In [20], a non-cooperative proactive caching scheme in the RSUs was proposed to minimize the communication latency in VANETs, considering the effect of the vehicle velocity. In order to minimize the total predicted delay across the network, the optimization problem with the sub-optimal caching policy is formulated and solved by the greedy algorithm. In [21], A CCN dwell-time collaborative caching approach focused on the V2V in dynamic network environments is proposed. It considered the mobility, relevance of vehicles in a connected vehicle, and the dwell time of content on network nodes under the request of Poisson arrival collaborative caching. The developed scheme enhanced the caching hit-rate, reduced user acquisition delay, and improved overall network performance. A cooperative superposed transmission (CST) scheme employed from non-orthogonal multiple access (NOMA) is proposed in [22]. In the proposed CST, two vehicles superpose their signal using the same network resources without interfering each other. In order to achieve high reliability and low latency in a variety of road environments, new power control and user pairing algorithms were developed.

In [23], [24], adaptive and dynamic wireless content caching along with multicast beamforming were investigated on the internet of vehicles (IoV) based vehicular edge networks. The relaxed linear programming methods (LP) and successive convex approximation (SCA) are used to solve a nonconvex multicast beamforming problem. The joint V2V-assisted clustering enhanced network efficiency in power savings, content caching, and vehicle sharing. A cooperative caching scheme in a multi-tier heterogeneous vehicular network (H-VNet) was proposed in [25] to enhance content delivery services while reducing transmission delay and service cost for connected vehicles. The presented scheme enables vehicles to fetch a single content from several caching servers cooperatively, taking into account cross-tier cooperation and vehicle mobility. The proposed algorithm was

optimized by deciding the best cooperative content placement strategy, which specifies the placement locations and proportions for all contents.

Hybrid vehicular network topology, including VLC, mmWave, and RF, have recently presented as efficient and reliable hybrid system [26]–[29]. The hybrid system is expected to significantly enhance the vehicle-to-everything (V2X) networks, which should be extremely intelligent and capable of simultaneously supporting ultra-fast, high-reliable, and low-latency wide information exchange. In [26], the distributed and non-cooperative topology control were investigated in integrated VLC/RF VANET. A topology control algorithm is proposed to manage the resource between the RF and VLC links and realize efficient and reliable hybrid topology. The proposed algorithm is modeled as a potential game to generate a VANET topology that realizes a tradeoff between the delay and power consumption via RF and VLC. The results showed that the topology control algorithm significantly reduced power consumption and interference among links while maintaining delay-limited connectivity. In [27], a proactive caching algorithm that uses the VLC system is proposed in VANET to increase the caching gain, reduce the blocking probability and improve the network throughput. The results have shown that the VLC system yields significant performance. In [28], the astochastic geometry framework for caching in mmWave V2X networks is proposed and validated by Monte Carlo simulation. This framework is used to study the effect of base station density, vehicular density, and caching size on the network performance in terms of delay and connectivity.

III. SYSTEM MODEL

The proposed system model is shown in Figure 1. It contains a set of vehicles $\mathcal{V} = \{1, 2, \ldots, V\}$ are moving in an area covered by a mobile base station. Assuming the u_v is the speed of the vehicle, t_v is the time spent traveling on the road, and each vehicle is equipped with a memory of size Z_v.

In the proposed system, we applied a platoon-based mobility model presented in [12]. Since the vehicles are inherently
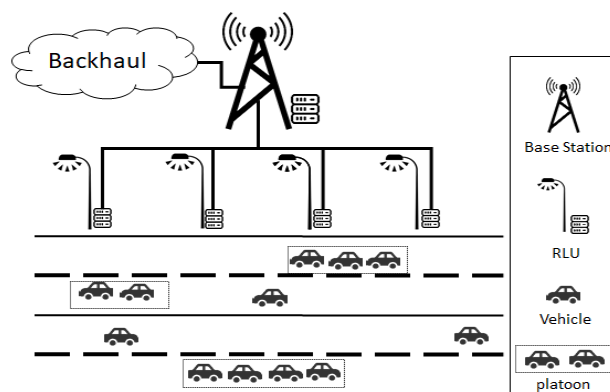

FIGURE 1. System model.

moving together, they are forming a group with their platoon. Platoons are constructed by enabling the vehicles to adopt specified patterns. Each group of vehicles constructs $\mathcal{G} = \{g_1, g_2, \ldots, g_G\}$ and led by a specific vehicle called the platoon head (PH), and G is the total number of platoons. Each platoon has a number of vehicle N_p^g where $\sum_{g=1}^{G} N_p^g = V$. The data can be sent between vehicles in the platoon by V2V communications, whereas the communication range of each platoon is limited by the number of vehicles and coverage area.

A region covered by a set of mobile base stations (MBS) $\mathcal{B} = \{1, 2, \ldots, B\}$, and equipped with a limited memory size of Z_b. Each MBS is divided into a set of remote light units (RLU) $\mathcal{L} = \{1, 2, \ldots, L\}$. Assuming that each RLU is connected with a reliable link such as mmWave, FSO, an optical fiber with the nearest MBS. Each RLU decides to assign a lighting pole and use LEDs in the range d_l to communicate with vehicles with data rate α_l. Under the intelligent transport system (ITS), smart vehicles use GPS so that MBS can determine their positions, speeds, and directions. Furthermore, the MBS manages the handover of the vehicles between RLU.

In the proposed system, the RLU performs only as a relay where MBS receives the requests from a vehicle and then forwards them to the associated RLU. In the present system, each vehicle has a library includes a random set of data items $\mathcal{M} = \{1, 2, \ldots, M\}$. Assuming that all of the data items are the same size of F Mbits. We construct a demand profile for each vehicle, v, denoted by $\vec{p}_v := (p_v^1, p_v^2, \cdots, p_v^M)$. We assume all vehicles can act as content providers and requesters. During time T, caching dose not change in network and vehicle v will request any data item m from library $\mathcal{M}$ with probability p_v^m.

We consider the caching decisions for file m at vehicle v and MBS b are x_v^m and x_b^m, respectively. They could give by the following expressions

$$x_v^m \in \{0, 1\}, \quad \forall m \in \mathcal{M}, \forall v \in \mathcal{V} \tag{1}$$

$$x_b^m \in \{0, 1\}, \quad \forall m \in \mathcal{M}, \forall b \in \mathcal{B} \tag{2}$$

If the item m is not available in the local cache of the vehicle v, it means $x_v^m = 0$. While the item is available in the vehicle's local database, it means $x_v^m = 1$. Similarly, if the m item is not present in the local MBS cache, $x_b^m = 0$ while $x_b^m = 1$ if the m item is present. The total size of the cached items should be less than or equal to the storage size of the memory on both sides (vehicle or MBS). Therefore, we have,

$$\sum_{m=1}^{M} F x_v^m \leq Z_v, \quad \forall v \in \mathcal{V} \tag{3}$$

$$\sum_{m=1}^{M} F x_b^m \leq Z_b, \quad \forall b \in \mathcal{B} \tag{4}$$

This research aims to find an optimal caching position in vehicles x_v^m and MBS x_b^m based on different scenarios. First, the vehicles are equipped with cache storage, which groups

the vehicles and enables them to communicate together (intra-platoon communications). Second, the vehicles at other platoons are equipped with cached items. If not all vehicles have cached items, they relay the required items to adjacent platoons (inter-platoon communications). Third, if the item does not exist in any vehicles in neighboring platoons, it will forward to the RLU, which fetches the data from the associated MBS and then passes it to the requested vehicle. Finally, vehicles help speed up the process by caching items and passing through distributed areas.

IV. PROBLEM FORMULATION

In this section, we introduce various models for our problem in order to detail it fully. The caching used in the vehicular layer is introduced with simple and general scenarios. Once we show the scenario where the system has RLU in serving vehicles, we then show a proactive caching scenario. This discussion of joint VLC and RF proactive caching concludes with a proactive caching scenario and complexity analysis.

A. VEHICULAR PROACTIVE CACHING VIA V2V

To arrive at proactive caching insights, we developed the following process: We first present the process for requesting flow and then use that to obtain insight into retrieval time in the toy scenario.

1) REQUESTING FLOW

Vehicles are able to access the backhaul network by connecting the MBS via V2I links. Vehicles can communicate with each other across vehicle networks via V2V communications with data rate of α_v Mbps. When a vehicle enters a distributed network, it requests that a particular data item be served/performed within the appropriate time-frame and resources by which the node provides that data item. The requested list will be satisfied with the fetching time of τ_f from its local cache if this vehicle is able to retrieve the requested item from its previous use in its local cache. Otherwise, the request will be forwarded to the PH. It will search for the request in its platoon members. If the data is found at another member, the requested vehicle will receive the data via a V2V connection with time $\tau_v = F/\alpha_v$. Furthermore, the requested data item can be received from another platoon if it has already been cached. However, the recovery time of τ_p is greater than τ_v. If the requested data item was not available in the vehicle, the request would be fulfilled by the remote server with the τ_b. During this process, in regards to the content retrieval time when the requested content is cached on the vehicle, the platoon members, the neighbouring platoons, or the MBS are denoted by τ_f, τ_v, τ_p, or τ_b respectively. we assume τ_f is the lowest, τ_v less than τ_p and τ_b is highest time.

2) A TOY SCENARIO VEHICULAR PROACTIVE CACHING

A toy scenario is considered to clarify our system. In this case, we assume that one platoon contains two vehicles with a memory size that can cache one file. These two files are

TABLE 1. All caching combination of toy scenario.

solution	x_1^1	x_1^2	x_2^1	x_2^2	W
sol 1	0	0	0	0	$\tau_b(p_1^1 + p_1^2 + p_2^1 + p_2^2)$
sol 2	1	0	0	0	$\tau_f p_1^1 + \tau_v p_1^2 + \tau_b(p_2^1 + p_2^2) + c_v$
sol 3	0	1	0	0	$\tau_f p_1^1 + \tau_v p_2^2 + \tau_b(p_1^1 + p_2^2) + c_v$
sol 4	1	1	0	0	Excluded due to memory size
sol 5	0	0	1	0	$\tau_v p_1^1 + \tau_f p_2^1 + \tau_b(p_1^2 + p_2^2) + c_v$
sol 6	1	0	1	0	$\tau_f(p_1^1 + p_2^1) + \tau_b(p_1^2 + p_2^2) + 2c_v$
sol 7	0	1	1	0	$\tau_f(p_2^1 + p_2^2) + \tau_v(p_1^1 + p_2^2) + 2c_v$
sol 8	1	1	1	0	Excluded due to memory size
sol 9	0	0	0	1	$\tau_b(p_1^1 + p_2^1) + \tau_v p_1^2 + \tau_f p_2^2 + c_v$
sol 10	1	0	0	1	$\tau_f(p_1^1 + p_2^1) + \tau_v(p_1^2 + p_2^2) + 2c_v$
sol 11	0	1	0	1	$\tau_b(p_1^1 + p_2^1) + \tau_f(p_1^2 + p_2^2) + 2c_v$
sol 12	1	1	0	1	Excluded due to memory size
sol 13	0	0	1	1	Excluded due to memory size
sol 14	1	0	1	1	Excluded due to memory size
sol 15	0	1	1	1	Excluded due to memory size
sol 16	1	1	1	1	Excluded due to memory size

located in the content library, and vehicle requests to utilize them have a different probability. The expected retrieval time for the vehicle $v = 1$ is as follows:

$$W_1 = p_1^1\left[x_1^1\tau_f + (1 - x_1^1)\left(x_2^1\tau_v + (1 - x_2^1)\tau_b\right)\right]$$
$$+ p_1^2\left[x_1^2\tau_f + (1 - x_1^2)\left(x_2^2\tau_v + (1 - x_2^2)\tau_b\right)\right]$$
$$+ c_v(x_1^1 + x_1^2) \tag{5}$$

Moreover, the same of $v = 2$, the total expected retrieval time is

$$W = p_1^1\left[x_1^1\tau_f + (1 - x_1^1)\left(x_2^1\tau_v + (1 - x_2^1)\tau_b\right)\right]$$
$$+ p_1^2\left[x_1^2\tau_f + (1 - x_1^2)\left(x_2^2\tau_v + (1 - x_2^2)\tau_b\right)\right]$$
$$+ p_2^1\left[x_2^1\tau_f + (1 - x_2^1)\left(x_1^1\tau_v + (1 - x_1^1)\tau_b\right)\right]$$
$$+ p_2^2\left[x_2^2\tau_f + (1 - x_2^2)\left(x_1^2\tau_v + (1 - x_1^2)\tau_b\right)\right]$$
$$+ c_v(x_1^1 + x_1^2 + x_2^1 + x_2^2) \tag{6}$$

Therefore, the optimal caching decision is the one that solves the following optimization problem:

$$\underset{x_1^1, x_1^2, x_2^1, x_2^2}{\text{minimize } W}$$
$$\text{subject to } F(x_1^1 + x_1^2) \leq Z_v$$
$$F(x_2^1 + x_2^2) \leq Z_v$$
$$x_1^1, x_1^2, x_2^1, x_2^2 \in \{0, 1\} \tag{7}$$

The network coordinator can reach the optimal solution by first identifying all possible solutions and then selecting the one that meets the minimum expected retrieval time, known as a heuristic solution. The following table illustrates all possible combinations: The minimum value of expected retrieval time for the optimal solution (given specified values for c_v, τ_b, τ_v, τ_f and p_v^m), where $W(\text{solution}^*) < W(\text{any-solution})$.

Case 1: Vehicle 1 decision when the vehicle 2 does not cache any file $x_2^1 = 0, x_2^2 = 0$. The minimum value of expected retrieval time calculates based on the following

steps:

$$W_1 = p_1^1\left[x_1^1\tau_f + (1 - x_1^1)\tau_b\right]$$
$$+ p_1^2\left[x_1^2\tau_f + (1 - x_1^2)\tau_b\right] + c_v(x_1^1 + x_1^2) \tag{8}$$

The caching analysis for vehicle 1 is shown in Table 2 while the decision is followed by the proceeding presented in Table 3.

TABLE 2. Caching analysis at vehicle 1 when vehicle 2 has no caching.

$x_1^1 = 0, x_1^2 = 0$	$W_1 = p_1^1\tau_b + p_1^2\tau_b$
$x_1^1 = 1, x_1^2 = 0$	$W_1 = p_1^1\tau_f + p_1^2\tau_b + c_v$
$x_1^1 = 0, x_1^2 = 1$	$W_1 = p_1^1\tau_b + p_1^2\tau_f + c_v$

TABLE 3. Caching decision at vehicle 1 when vehicle 2 has no caching.

No cache	if $p_1^1 < \frac{c_v}{\tau_b - \tau_f}, p_1^2 < \frac{c_v}{\tau_b - \tau_f}$
cache file 1 only $x_1^1 = 1$	if $p_1^1 > \frac{c_v}{\tau_v - \tau_f}, p_1^1 > p_1^2$
cache file 2 only $x_1^2 = 1$	if $p_1^2 > \frac{c_v}{\tau_b - \tau_f}, p_1^2 > p_1^1$

Case 2: Vehicle 1 decision when the vehicle 2 caches only file 1, $x_2^1 = 1$ and $x_2^2 = 0$. The minimum value of expected retrieval time calculates based on the following steps:

$$W_1 = p_1^1\left[x_1^1\tau_f + (1 - x_1^1)\tau_v\right]$$
$$+ p_1^2\left[x_1^2\tau_f + (1 - x_1^2)\tau_b\right] + c_v(x_1^1 + x_1^2) \tag{9}$$

The caching analysis for vehicle 1 is shown in Table 4 while the decision is followed by the proceeding presented in Table 5.

TABLE 4. Caching analysis at vehicle 1 when vehicle 2 caches only file 1.

$x_1^1 = 0, x_1^2 = 0$	$W_1 = p_1^1\tau_v + p_1^2\tau_b$
$x_1^1 = 1, x_1^2 = 0$	$W_1 = p_1^1\tau_f + p_1^2\tau_b + c_v$
$x_1^1 = 0, x_1^2 = 1$	$W_1 = p_1^1\tau_v + p_1^2\tau_f + c_v$

TABLE 5. Caching decision at vehicle 1 when vehicle 2 caches only file 1.

No cache	if $p_1^1 < \frac{c_v}{\tau_v - \tau_f}, p_1^2 < \frac{c_v}{\tau_b - \tau_f}$
cache file 1 only $x_1^1 = 1$	if $p_1^1 > \frac{c_v}{\tau_v - \tau_f}, p_1^1 > \frac{p_1^2(\tau_b - \tau_f)}{\tau_v - \tau_f}$
cache file 2 only $x_1^2 = 1$	if $p_1^2 > \frac{c_v}{\tau_v - \tau_f}, p_1^1 > \frac{p_1^1(\tau_b - \tau_f)}{\tau_v - \tau_f}$

According to these analysis, no cache will happen when $p_v^m < \frac{c_v}{\tau_b - \tau_f}$. In addition, if $p_v^m > \frac{c_v}{\tau_v - \tau_f}$ file m must be cache at vehicle v.

3) GENERAL SCENARIO VEHICULAR PROACTIVE CACHING
In a proactive scenario, we assume that the v vehicle requests a data item whenever the previous request has been completed. The following equation is used to calculate the time

to deliver the m content requested by the vehicle v in the g_k platoon.

$$W_v^m = p_v^m \left[x_v^m \tau_f + (1 - x_v^m) \left(\left\| \sum_{i \in g_k} x_i^m \right\|_0 \tau_v \right. \right.$$

$$+ (1 - \left\| \sum_{i \in g_k} x_i^m \right\|_0)(\left\| \sum_{j \in V} x_j^m \right\|_0 I_v^g \tau_p$$

$$\left. \left. + (1 - \left\| \sum_{j \in V} x_j^m \right\|_0)(1 - I_v^g \tau_b)) \right) \right] + c_v x_v^m \quad (10)$$

where $\|f(.)\|_0$ equals 0 if $f(.) = 0$, and equals 1 otherwise.

$$\|f(.)\|_0 = \begin{cases} 1, & f(.) > 1, \\ 0, & f(.) = 1 \end{cases} \quad (11)$$

and I_p^g is indicator of vehicle v meets platoon g

$$I_v^g = \begin{cases} 1, & \text{with probability } q_v^g, \\ 0, & \text{with probability } 1 - q_v^g. \end{cases} \quad (12)$$

Therefore, the total expected latency of network is following as:

$$W = \frac{1}{V} \sum_{v=1}^{V} \sum_{m=1}^{M} W_v^m \quad (13)$$

The requested platoon must meet another platoon to transfer the item from one platoon to another. To do this, the probability of two platoons meeting each other is q_v^g. The Poisson distribution model determines the average number of platoons in a particular area.

$$P(N_v = k) = \frac{n_v^k}{k!} e^{-n_v} (k = 0, 1, \ldots) \quad (14)$$

where $n_v := \frac{C}{\lambda}$ is the average number of platoons in a vehicle communication range C and the average number of vehicles is λ. Accordingly, the probability of meeting another platoon is

$$q_v^g = 1 - q_v^{nm} \quad (15)$$

where

$$q_v^{nm} = P(N_v = 0) \times \text{Prob}(u_v \le u_i | t_v \ge t_i : \forall i \in V) \quad (16)$$

The $\text{Prob}(u_v \le u_i | t_v \ge t_i : \forall i \in V)$ is given by

$$Pr(u_v \le u_i | t_v \ge t_i) = \prod_{i=1}^{|G|} Prob(u_v \le u_i)(Pr(u_v \le u_i))^{|G|} \quad (17)$$

where

$$Pr(u_v \le u_i) = Pr(u_v - u_i \le 0) \quad (18)$$

As a result of u_v and u_i have the same distribution $f(u)$, the $\text{Prob}(u_v - u_i \le 0) = 0.5$. The optimal caching decision will be the solution of the following optimization problem:

$$\underset{x_s^m, x_v^m}{0 \text{ minimize } W}$$
$$\text{subject to } 1, \; 3. \quad (19)$$

We aim to minimize the problem that ran previously by determining the optimal caching placement in vehicles. The mixed-integer constrained problem is written as Eq. 7. Thus, a genetic algorithm can be solved efficiently, which is often the case when solving this problem. By using the analytical approach in a toy scenario, it can be stated that caching decision is biased to the file with the highest request probability. We proposed an algorithm 1 known as caching in which we first find the file that contains the highest probability of each vehicle, which is $\vec{\Omega}$, and then the index of that vehicle in $\vec{\theta}$. After that, the maximum of $\vec{\Omega}$ and its index v have been calculated. If there is available cache memory and files have not been cached, we will cache θ_v in the vehicle v. In that case, $\vec{\theta}_v$ will be excluded, and repeat these steps until they reach minimum retrieval time.

Algorithm 1 Sub-Optimal Vehicular Proactive Caching in General Scenario

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Input: $\vec{p}_v, Z_v, c_v, \tau_b, \tau_v, \tau_f, \hat{W}, \forall v \in V, \forall m \in \mathcal{M}$
set $W_{old} = 10000$ and $W_{new} = \text{NoCache}$
while $W_{old} > W_{new}$ **do**
    set $W_{old} = W_{new}$
    get max. of $\vec{p}_v$ in $\vec{\Omega}$ and its index in $\vec{\theta}$ $\forall v \in V$
    get max. of $\vec{\Omega}$ in p_{max} and set its index in v
    if $p_{max} > \frac{c_v}{\tau_b - \tau_f}$ **then**
        if $\sum_{m=1}^{M} x_v^m \le Z_v$ **then**
            $x_v^{\theta_v} = 1$
        end
        $p_v^{\theta_v} = 0, \forall v \in V$
    end
    update W_{new}
end
Output x_v^m

B. VEHICULAR PROACTIVE CACHING VIA RLU

In this scenario, we assume that no cache is installed on any vehicles and there are moving in the zone covered by RLUs. When the vehicle requests a cached item, it will be served using the VLC link is given by F/α_l as there is availability in RLU. Otherwise, it will take only access time $\hat{\tau}_b$, $\hat{\tau}_b = F/\alpha_b$. In case this content does not cache, vehicle will receive data from RLU or the MBS via the RF link based on RLU connectivity by $\tau_l + \tau$, $\tau_b = \hat{\tau}_b + \tau$ respectively and the total delay time in backhaul network is presented as τ. Where α_l is the data rate of the VLC link in Mbps, and α_b is the data rate of the RF link in Mbps as presented in [27]. Accordingly, the expected retrieval time can be formulated as

$$\hat{W}_v^m = p_v^m q_v^b \left[x_b^m \left(J_v^l \tau_l + (1 - J_v^l) \hat{\tau}_b \right) \right.$$
$$\left. + (1 - x_b^m) \left(J_v^l (\tau_l + \tau) + (1 - J_v^l)(\tau_b) \right) \right] \quad (20)$$

where J_v^l is the indicator variable of available channel at RLU to communicate with vehicle, it can be represented

as follow

$$J_v^l = \begin{cases} 1, & \text{with probability } y_v^l, \\ 0, & \text{with probability } 1 - y_v^l. \end{cases} \quad (21)$$

The probability y_v^l of vehicle v can communicate with RLU l successfully when one vehicle is in the coverage of the RLU l. We assume that, the probability follows Poisson Eq 14 with $n_l := d_l/\lambda$ is the average number of vehicle in RLU. Furthermore, the RLU communicates only with one vehicle at a time. Therefore y_v^l given as

$$y_v^l = P(N_l = 1) = n_l e^{-n_l} \quad (22)$$

Therefore, the total expected retrieval time is given by

$$\hat{W} = \frac{1}{V} \sum_{v=1}^{V} \sum_{b=1}^{B} \sum_{m=1}^{M} \hat{W}_v^m + c_b \sum_{b=1}^{B} \sum_{m=1}^{M} x_b^m \quad (23)$$

The optimal caching decision in the scenario of proactive caching via RLU is the solution of the following optimization problem

$$\underset{x_b^m}{\text{minimize}} \ \hat{W}$$
$$\text{subject to } 2, \ 4. \quad (24)$$

C. JOINT PROACTIVE CACHING

In this scenario, we include the vehicular proactive caching techniques of V2V and RLU. The process of item retrieval is divided into 4 stages. 1) The item m is in the cache of the requested Vehicle. It takes time τ_f, if not exist move to stage 2, 2) The item m is in the cache of another Vehicle within the same platoon. It takes time τ_v, if not exist move to stage 3, 3) The item m is in the cache in MSB. It takes time τ_l if RLU has an available channel. Otherwise, it takes $\hat{\tau}_b$, if not exist move to stage 4, 4) The Vehicle is covered by a backhaul server. It takes time $\tau_l + \tau$ to be served via RLU. Otherwise, the Vehicle fetches the item m directly from the MBS with time τ_b. Accordingly, the expected retrieval time can be represented as

$$\tilde{W}_v^m = p_v^m \Bigg[x_v^m \tau_f + (1 - x_v^m)\Bigg(\Bigg\| \sum_{i \in g_k} x_i^m \Bigg\|_0 \tau_v$$
$$+ (1 - \Bigg\| \sum_{i \in g_k} x_i^m \Bigg\|_0)\big(x_b^m(J_v^l \tau_l + (1 - J_v^l)\hat{\tau}_b)$$
$$+ (1 - x_b^m)(J_v^l(\tau_l + \tau) + (1 - J_v^l)(\tau_b)))\Bigg) \Bigg] \quad (25)$$

The overall retrieval time can be written as

$$\tilde{W} = \sum_{m=1}^{V} \sum_{m=1}^{M} \tilde{W}_v^m + c_b \sum_{m=1}^{M} x_b^m + c_v \sum_{m=1}^{M} x_v^m \quad (26)$$

Finally, we apply superposition principle to find the optimal value of (24).

1) COMPLEXITY ANALYSIS

Brute force (which involves searching exhaustively) has exponential computational power, making the problem extremely difficult to solve if the number of vehicles or files increases. It generates all combinations of the solution then computes W and $\hat{W}$ for each solution to find the minimum value solution. For example, in a vehicular layer system, if 2 vehicles and 3 files are present, the number of all combinations is $2^6 = 2^{MV}$. Although the complexity of this algorithm is $\mathcal{O}(2^{MV})$, and it can find the optimal solution. Additionally, the Genetic algorithm its complexity will reach $\mathcal{O}(2^{MV})$ in the worst-case. However, on the other hand, the proposed algorithm at each iteration will search for maximum request probability, which takes MV, and the maximum number of iterations is M all files will cache so that the complexity will be $\mathcal{O}(VM^2)$.

The proposed algorithm 2 uses to find the optimal files that can be cached at MBS. For MBS b the complexity of brute force algorithm is $\mathcal{O}(2^{M.V})$, in besides algorithm 2 has $\mathcal{O}(Z_b MV)$. The joint proactive caching system runs the complexity of the algorithm $\mathcal{O}(VM^2 + Z_b VM)$. As long as the number of files is large, i.e., $M \gg Z_b$, the complexity becomes $\mathcal{O}(VM^2)$.

Accordingly, the complexity of different scenarios is summarized in Table 6.

Algorithm 2 Sub-Optimal Vehicular Proactive Caching via RLU for MBS b

---
Input: $F, \vec{p}_v, Z_b, c_b, \tau_b, \tau_l, x_b^m \ \forall v \in V, \ \forall m \in \mathcal{M}$

Calculate $\vec{p}_b := \{p_l^1, p_l^2, \ldots, p_b^m, \ldots, p_b^M\};$

$p_b^m = \frac{1}{V} \sum_{v=1}^{V} p_v^m, \forall m \in \mathcal{M}$
set $W_{old} = \text{NoCache}$
set $k = 1$
while *TRUE* **do**
    Get $h = argmax(\vec{p}_b)$
    Remove $\vec{p}_b(h)$
    set $x_b^h = 1$
    Calculate $\hat{W}$ from Equ(23)
    set $W_{new} = \hat{W}$
    if $W_{new} \geq W_{old}$ *OR* $F * k > Z_b$ **then**
        set $x_b^h = 0$
        break
    end
    set $W_{old} = W_{new}$
    set $k = k + 1$
end
Output x_b^m

TABLE 6. Complexity analysis.

	Brute force	proposed
V2V network	$\mathcal{O}(2^{VM})$	$\mathcal{O}(VM^2)$
RLU network	$\mathcal{O}(2^{VM})$	$\mathcal{O}(Z_b VM)$
Joint network	$\mathcal{O}(2^{VM})$	$\mathcal{O}(VM^2)$

V. SIMULATION RESULTS AND DISCUSSION

In this section, a comparative study between different catching scenarios (no caching, V2V, RLU and joint proactive caching) presented. In order to locate vehicles, we assume that they are uniformly distributed throughout the entire region. The velocity of the vehicles is diverse and independent over the place. The vehicle distribution is generated by the following truncated Gaussian distribution with mean μ and variance σ^2.

$$f(u) = \frac{2\exp\left(\frac{-(u-\mu)^2}{2\sigma^2}\right)}{\sqrt{2\pi\sigma^2}\left(\mathrm{erf}\left(\frac{u_{\max}-\mu}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{u_{\min}-\mu}{\sigma\sqrt{2}}\right)\right)}. \quad (27)$$

where $u_{\min}$ is the minimum velocity and $u_{\max}$ is the maximum velocity of vehicle v. Furthermore, we consider the probability of vehicle items requests follows a Zipf distribution. Finally, the simulation parameters are presented in Table 7.

TABLE 7. System parameter per one platoon.

Parameter	Symbol	number
MBS	L	1
RLU	R	25
Vehicles	V	10 to 100
Files per vehicle	M	200 to 2200
Platoon size	G	1 to 48
fetching time	τ_f	0.001
vehicle communication time	τ_v	0.04
RLU communication time	τ_l	0.017
MBS communication time	$\hat{\tau}_b$	0.2
Backhaul communication time	τ_b	3
Zipf parameter	γ_v	0.5 to 2
vehicle caching cost	c_v	0.2
MBS caching cost	c_b	0.2
Vehicle caching size	Z_v	20
MBS caching size	Z_b	200

Figure 2 shows the effect of varying the number of vehicles on the expected retrieval time in different scenarios considering the library size of 1000 files per vehicle, and each platoon could contain up to 8 vehicles. Since we can see, the optimal retrieval time can be achieved when the joint proactive caching between the platoon and RLU is applied. The usage of RLU only gives a better time if the number of vehicles is less than 22. However, if the number of vehicles increases beyond this value, it will be beneficial to use the joint caching of the platoon and the RLU.

The impact of an increase in the number of files is shown in Figure 3 for 48 vehicles and 8 vehicles per platoon. As we have seen, the increase in the number of files impacts the operation of the platoon. With 450 files or less, proactive caching using only the RLU achieves better performance. However, when there is an increase in the number of files, the joint proactive caching uses platoon and RLU will perform better than other scenarios.

Figure 4 illustrates the platoon size effect, which can be visualized using the 48 vehicle platoon and 1000 file per vehicle. The highest level of performance is still when the joint proactive caching is used. The same performance could be achieved when the caching in the platoon scenario is applied,
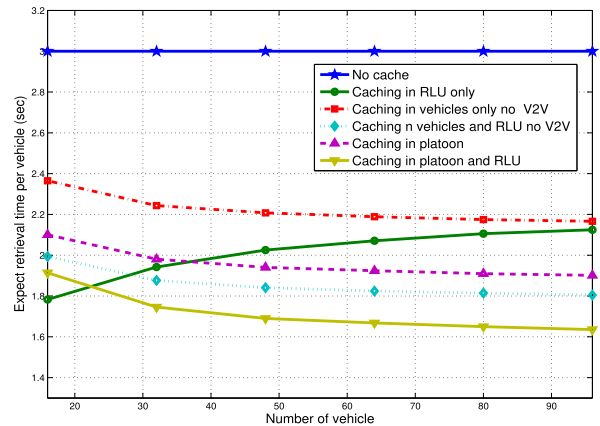

FIGURE 2. Evaluation of different caching schemes with number of vehicles, considering 1000 files per vehicle and 8 platoons.
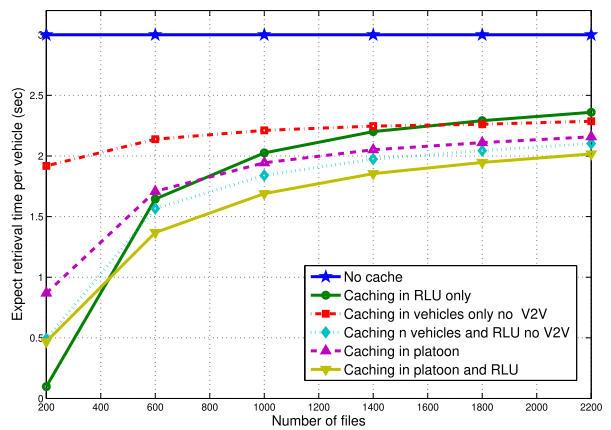

FIGURE 3. Evaluation of different caching schemes with number of file, considering 48 vehicles and 8 platoons.
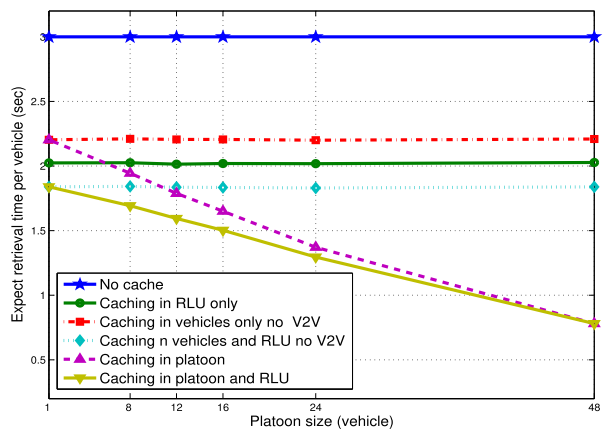

FIGURE 4. Evaluation of different caching schemes with platoon size, considering 1000 files per vehicle and 48 vehicles in each platoon.

and all vehicles are assigned to the same platoon. In Figure 5, we assumed that the number of cached files per vehicle is reduced to 25 (very low). The RLU caching only will give a better performance when the platoon number is less than 14. However, if the number of platoons increases beyond this
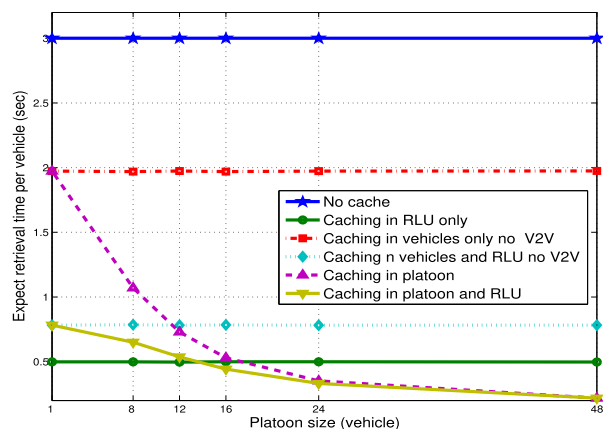
FIGURE 5. Evaluation of different caching schemes with platoon size, considering 25 files per vehicle and 48 vehicles in each platoon.

value, the caching in the platoon and joint proactive caching scenarios is much better.

VI. CONCLUSION

In this paper, caching placement schemes that jointly consider caching of the vehicles and MBS layers are proposed. We studied caching placement in three scenarios, V2V, RLU, and joint proactive caching. The caching placement for all scenarios which minimizes the expected retrieval time is formulated as an optimization problem. Based on the demand of the user and the mobility model, the optimal placement of the caching is determined to shorten the latency in responding to vehicle requirements. Non-cooperative and cooperative vehicles with V2V communication shall be considered. Using the high data rate of VLC in the vehicle networks increases the caching capability of both models. In addition, we illustrated a sub-optimal algorithm to solve optimization problems and then compared it to an optimum brute force solver and a sub-optimal genetic algorithm. Furthermore, the impact of the number of files, the density of the vehicle, and the size of the platoon are studied. Numerical results showed that the RLU improved the proactive caching performance when the number of vehicles is low (less than 25). However, if the number of vehicles increased, the joint proactive caching scheme provided better performance. The V2V with a platoon is better to be used when the number of vehicles per platoon exceed 10.

Our future work includes the following points. We will investigate the impact of dynamic vehicle velocities, which follow a particular, probabilistic distribution, on the effectiveness of each caching scheme employed. Furthermore, we plan to utilize machine learning algorithms, such as probabilistic reasoning through neural networks, to extract, maintain, update, and utilize information related to cached contents and potential hosting zones in order to improve the performance of the contents retrieval process. We plan to investigate the impact of updating cached contents and networking operations-related overhead on the time complexity of the

performance analysis of the studied caching schemes. Furthermore, considering vehicle mobility across multiple roads can help us manage proactive caching more effectively. Also, considering the cooperating with multiple edge servers might improve data sharing and contribute more to autonomous vehicles.

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