IMPROVING VIDEO STREAMING QUALITY IN 5G ENABLED VEHICULAR NETWORKS

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ABSTRACT

The 5G mobile communication technologies are the most prominent candidates for vehicular networks to support various types of applications. In this article, we describe several 5G technologies and how these technologies support various types of vehicular applications. Since high-quality video streaming over vehicular networks is one of the most popular on-road entertainment applications for passengers, this article discusses the challenges of video streaming over 5G enabled vehicular networks. To achieve better video streaming quality, we introduce a double-buffer system to mitigate the delay effect due to a vehicle's frequent handoffs among 5G small cells and the intermittent connection effect resulting from millimeter-wave propagation features. We also discuss potential future work on joint optimization of buffer space and bandwidth allocation for video streaming, and maintaining connectivity for real-time applications in 5G enabled vehicular networks.

INTRODUCTION

Vehicular networks are playing an increasing role in the world since people spend significant amounts of time on the road [1, 2]. As vehicles have continued to evolve, vehicular networks rely on wireless communications among vehicles and infrastructure to provide passengers various types of applications on safety, traffic control, entertainment, and so on [3]. 5G mobile networks can provide ubiquitous coverage for vehicles to access, ultra-low latency for vehicular safety applications, and very high capacity to support a large number of vehicles and bandwidth-intensive applications (e.g., uncompressed mobile video streaming needs the data rate of 1.78 or 3.56 Gb/s) [4, 5]. Therefore, 5G technologies are promising candidates for vehicular networks.

5G mobile networks have to achieve huge capacity (e.g., 1000 times that of 4G mobile networks) to satisfy the dramatic increase of data traffic brought by new applications and the explosive growth in the number of wireless devices [5]. In order to overcome the bandwidth shortage in the saturated microwave spectrum, millimeter-wave (mmWave) communication with multi-gigahertz bandwidth availability can achieve super large capacity and much higher transmission rate for 5G mobile networks [5, 6]. Therefore, 5G mobile networks are expected to use mmWave communication as the underlying transmission technology. Resulting from mmWave propagation features and user mobility, mmWave-based 5G mobile networks have a number of characteristics [6]:

- Frequent handoffs for users moving among different mmWave cells with smaller size
- Directional transmission/receiption because mmWave communication uses directional antennas to combat the high propagation loss
- Intermittent connection due to limited penetration capability and diffraction ability at mmWave spectrum

These characteristics can have a great impact on the quality of applications in 5G enabled vehicular networks.

Video streaming is one of the most frequently launched applications for passengers' entertainment [2, 7, 8], especially during long trips. Nowadays, most data traffic is produced by video applications [9]. Therefore, maintaining video streaming quality over 5G enabled vehicular networks can have a great impact on passengers' trip experiences. Due to the mentioned characteristics of mmWave-based 5G mobile networks, several factors can affect video streaming quality over 5G enabled vehicular networks. First, frequent handoffs can generate frequent video freezing resulting from frequently rebuilding the connections from a remote video server to moving vehicles through different mmWave base stations. Second, directional connectivity is difficult to maintain since it is a challenging issue to keep directional antenna beams directed toward each other for high-mobility scenarios. Both factors can cause intermittent connection, making video streaming discontinuous over 5G enabled vehicular networks.

This article focuses on improving video streaming quality over 5G enabled vehicular networks. We discuss the technologies involved in 5G networks, how these technologies support various types of vehicular applications, and the challenges of video steaming over 5G enabled vehicular networks. An integrated double-buffer system is introduced to improve the quality of vehicular video streaming by mitigating the effect of intermittent mmWave connection and the effect of frequent handoff at the cost of extra buffer memory. Then the article is concluded with a summary and a brief discussion of future work.

5G ENABLED VEHICULAR NETWORKS

Emerging 5G technologies can offer ubiquitous connections to vehicles with sufficient bandwidth and ultra-low latency at lowered energy cost [8].

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Performance	5G technologies
Capacity improvement, high data rate (1000 times 4G capacity)	MmWave communication, massive MIMO, multi-tier networks, D2D communication, advanced channel coding
Reducing delay (around 1 ms for real-time applications)	Full-duplex communication, SDN, D2D communication, cloud RAN
Reducing energy cost per link (with 100 times link rate)	Power control, small cell, higher spectrum (mmWave)
Connection reliability improvement (reducing link outage rate)	Heterogeneous and multi-tier networks
Advanced applications (e.g., Internet of Things, interactive applications)	Cloud RAN, network virtualization, software defined networks

TABLE 1. 5G performance with corresponding enabling technologies.

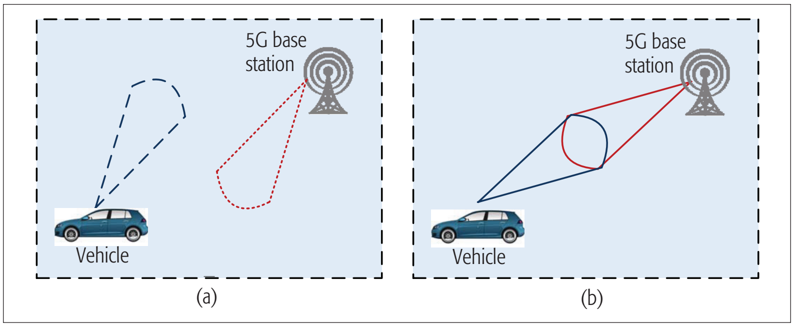

FIGURE 1. Connectivity with directional antenna: a) without directional connectivity; b) with directional connectivity.

Thus, 5G technologies can support rich engaged service applications for vehicles. Even more, vehicular networks can be merged into current Internet structure by 5G technologies. Therefore, vehicular networks can be well supported by 5G technologies.

5G TECHNOLOGIES

5G technologies are expected to bring significant improvements on network performance [5, 10] in order to support various types of new applications (haptic communication, uncompressed video streaming, etc.) with more stringent quality of service (QoS) requirements. Specifically, in order to support bandwidth-intensive applications and a huge number of wireless devices, 5G mobile networks need to greatly increase network capacity and the transmission data rate. MmWave communication can increase network capacity and transmission data rate because of the large spectrum [6, 9]. Massive multiple-input multiple-output (MIMO) and multi-tier networks can improve network capacity by exploiting spatial reuse [5]. Also, some real-time applications require latencies on the order of 1 ms, while current 4G round-trip latencies are on the order of about 15 ms. Device-to-device (D2D) communication can reduce delay by enabling direct communication between two devices in the same cell without involving a base station [6]. Cloud-based radio access networks (C-RAN) enable joint process and control over the networks to decrease the handover latency [11]. Full-duplex (FD) communication is able to reduce the latency by simultaneously receiving feedback signals from the receiver while transmitting [4]. Table 1 summarizes the key enabling 5G technologies and the corresponding performance improvements (or supported new applications) [1, 4, 5, 11, 12]. Please note that each item in Table 1 indicates the performance requirement in a specific dimension, and not all of the performance requirements need to be satisfied simultaneously.

Among these 5G technologies, mmWave communication can reach abundant network capacity, which is the primary motivation of 5G networks [6]. MmWave spectrum from 30 GHz to 300 GHz has several fundamental propagation characteristics [5, 6]. First, mmWave communication has high propagation loss because of the high frequency and oxygen absorption. Small cells (with cell size around 100–200 m) are adopted to cover the service area. Therefore, mobile users have more frequent handoffs due to the smaller cell size. Second, a high-gain directional antenna is implemented to combat the severe propagation loss. As shown in Fig. 1, the ideal "flat-top" antenna model is adopted for directional communication in this article. The transmitter and the receiver need to direct their beams toward each other in order to maintain directional connectivity. If the transmitter and receiver are out of each other's beamwidth, the transmission data rate would be decreased significantly due to the high antenna directivity and the high propagation loss. Thus, we consider that the data rate of the link is approaching zero compared with the achieved data rate of multiple gigabits per second when the transmitter and receiver direct their beams toward each other. Each vehicle has short connection time to the base station considering high user mobility, antenna directivity, and smaller cell size. Third, resulting from the short wavelength, mmWave communication has limited capability to diffract around obstacles. MmWave signal also has limited penetration capability.

VEHICULAR APPLICATIONS IN 5G NETWORKS

5G technologies have performance achievements in delay, capacity, reliability, and data rate. This section presents different types of vehicular applications and how these applications can be supported in 5G enabled vehicular networks.

Two types of applications can be defined in vehicular networks: *safety applications* and *non-safety applications*. Safety applications (e.g., safety messaging, alarming, and warning) should be offered in all vehicles and required to exchange status information with middle communication range to increase safety awareness. Safety applications in vehicular networks have strict latency constraints (on the order of a few milliseconds) and very high reliability requirements. As shown in Table 1, 5G mobile networks can achieve around 1 ms latency and provide reliable connection to support safety applications for vehicular networks.

Non-safety applications are related to traffic services and entertainment applications. Traffic services, combined with safety applications forming an intelligent transportation system (ITS), include traffic monitoring, congestion control, speed adjustment, maps download, parking payments, automatic tolling services, and so on. These applications collect information from vehicles spanning multiple kilometers and have relatively relaxed latency requirements while the information exchanges are heavy. 5G networks have cell-based structure to collect vehicle's information (vehicle's speed, location, etc.) and transmit the processed information (e.g., proper route, required speed limit) from a traffic service center to each vehicle or to multiple vehicles. For example, the C-RAN architecture in 5G can be used to collect traffic information, to determine the speed of vehicles in a centralized manner, and to deliver the speed information calculated by the cloud to vehicles in each cell. Another type of non-safety application is related to passenger entertainment to enjoy the trip, including video streaming and web browsing. These applications require Internet access through infrastructure. 5G networks have abundant capacity to support a large number of vehicles with video streaming applications requiring high data rate (on the order of multi-gigabits per second).

Video Streaming over 5G Enabled Vehicular Networks

Video Streaming Architecture

Video streaming is one of the major applications operating on vehicular networks for passenger entertainment. Figure 2 shows the considered structure of video streaming over 5G enabled vehicular networks in highway scenarios. Basically, the considered area is covered by 5G networks, and each vehicle has a wireless module to communicate with each 5G base station when the vehicle is associated with that 5G base station.

In Fig. 2, a number of mmWave base stations are deployed on the highway to provide seamless coverage for vehicles. Each mmWave base station is deployed in the center of each small cell and is associated with a number of vehicles moving on the highway. Since vehicles move towards a certain direction on the highway, the next associated mmWave base station for each vehicle is predictable. Both mmWave base stations and vehicles are equipped with directional antennas for transmission/reception. When vehicles (or passengers' wireless devices) request video streaming, the requests are forwarded to a remote video server by an mmWave base station through the Internet. Then the video data is transmitted to the mmWave base station and downloaded to vehicles via the mmWave channel. The above procedure generates the delay starting from the time the video streaming request is generated to the time video streaming data is received at vehicles, which could affect video streaming quality.

Challenges in Video Streaming

As discussed above, mmWave-based 5G networks have competitive advantages to support vehicular applications. However, the unique features of 5G enabled vehicular networks with mmWave communication can cause challenges in video streaming quality.

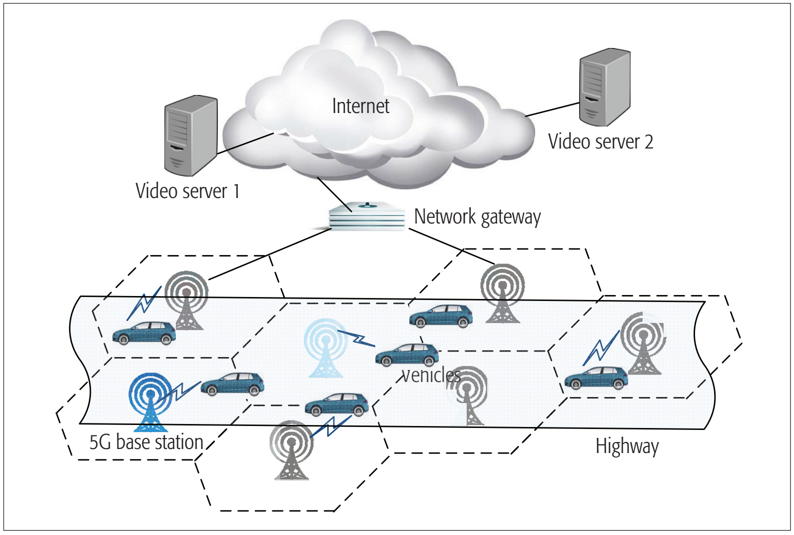

FIGURE 2. Structure of video streaming over 5G enabled vehicular networks.

At the mmWave base station, delay is the major impact of 5G enabled vehicular networks on video streaming. Since 5G networks have smaller cell sizes, vehicles with high speed would suffer from frequent handoffs and have to frequently rebuild the connections between vehicles and remote video servers via the Internet. As discussed previously, the procedures of rebuilding connections between vehicles and remote video servers introduce delay, which could result in vehicles entering a new cell not having available video data to play out and the video streaming being frozen. Since the directional connection is built if and only if both the mmWave base station and the vehicle are within each other's beamwidth, the mmWave connection sometimes can be disconnected if the directional antennas are not directed toward each other in high-mobility scenarios. Thus, only part of the duration for which the vehicle stays in the cell is used for video data transmission. This fact means that the delay has a worse impact on video streaming quality.

In the vehicle where video streaming is conducted by a video player, the video playout quality is mainly affected by intermittent mmWave connection. Because of limited diffraction capability, mmWave connection can be blocked by obstacles located in a line of sight (LOS) link. High penetration loss of mmWave signal through buildings and metal materials (e.g., 180 dB attenuation for concrete at 60 GHz) makes mmWave connection unavailable somewhere within (or around) a building. Communication between moving vehicles and base stations can be disconnected if their antenna beams are not tracked. Considering the high mobility of vehicles on highways, video streaming quality can be significantly affected by intermittent connection for the above reasons.

Related Work

Improving video streaming quality over wireless networks has been intensively investigated due to the limited network resource and high dynamics of wireless channels [2, 4, 8, 10, 13]. One type of research focuses on improving video streaming quality through efficient resource utilization [8, 13]. In [8], the bandwidths are dynamically allocated among all the users in the network under capacity constraints to maximize the bandwidth resource utilization. In [13], based on the network load characteristics, video streaming dynamically obtains network resources from both 4G networks and wireless local area networks (WLANs) to optimize the system utility.

Another type of research on improving video

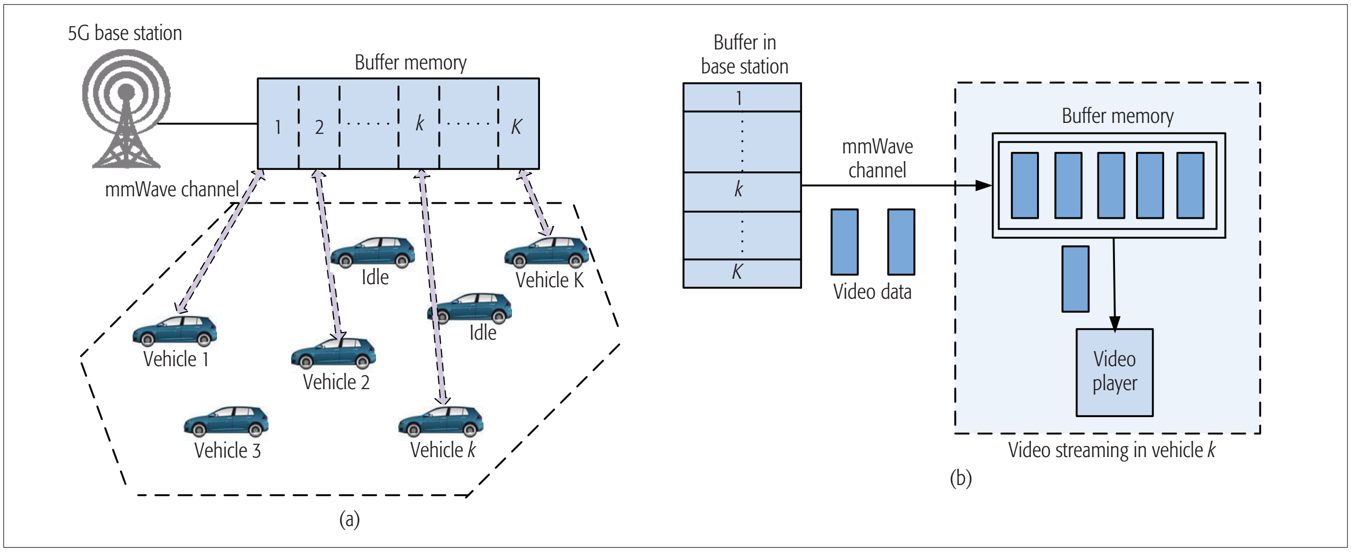

FIGURE 3. Double-buffer system for 5G enabled vehicular networks: a) buffer system at an mmWave base station; b) buffer system at each vehicle.

streaming quality is to pre-cache video content in the memory of base stations [2, 10]. In [2], a commercialized small-cell caching system is proposed to lease popular videos into base stations to mitigate redundant data transmissions over backhaul channels in heterogeneous networks (HetNets). In [10], a 5G-based paradigm is used to collect users' profiles and usage information to predict future video streaming requests in order to pre-load popular videos at base stations.

Buffering at mobile devices is another area of research to improve video streaming quality in vehicular networks. In [14], short-term burst transmission can be used to increase pre-buffering when mobile devices are approaching areas with vulnerable wireless channel quality. In [15], a buffer management scheme is proposed for mobile video streaming to minimize the cost of unconsumed video data. Most of the existing work on pre-buffering technologies considers the video streaming quality for each user. However, since high-quality video streaming applications are becoming popular and require high data rate, there are mutual impacts on the video streaming quality for different users under constrained network capacity.

Most of the existing work on improving video streaming quality (complex resource allocation mechanisms, using heterogeneous networks to provide better network connectivity, mechanisms to predict the most popular videos for pre-loading, etc.) involves heavy communication and/or computation overheads. These methods make the networks more complex. Since 5G networks are already complex by integrating many technologies to achieve the expected performance, applying these methods over 5G enabled vehicular networks would make the networks impractical to implement due to the complexity. In this article, we propose a novel method without complex network design for mmWave 5G enabled vehicular networks by using pre-caching at the mmWave base station and pre-buffering at mobile devices to achieve optimal bandwidth allocation and buffer management in terms of video streaming quality for all the users.

Double-Buffer System for Video Streaming

As discussed previously, mmWave communications bring challenges on video streaming over 5G enabled vehicular networks. In this section, a double-buffer system is introduced to deal with these challenges, considering that video streaming does not require real-time communications. Two buffer systems are implemented in mmWave base stations and vehicles (or passengers' mobile devices), respectively. Although the backbone networks have an impact on video streaming quality (e.g., video data package transmission from a remote video server to mmWave base stations), this article focuses on improving video streaming quality over 5G enabled vehicular networks. The buffer system implemented in mmWave base stations aims to mitigate frequent video streaming freeze due to frequent vehicle handoffs to rebuild connections to the remote video server. The buffer system in vehicles is used to eliminate the impact of high dynamics of mmWave connection on video streaming quality.

Buffer System at the 5G Base Station

To improve the quality of mobile video streaming over 5G enabled vehicular networks, a buffer system is implemented at the mmWave base station to pre-load the required video data from the remote video server and save the video data in the buffer installed in each base station. Vehicles entering a new cell can immediately have available video data, which mitigates the delay impact resulting from frequently rebuilding the connection to a remote video server as vehicles move among different cells. Figure 3a shows the buffer system architecture in each 5G base station. Each mmWave base station $\mathcal{S}_i$ (in total M base stations) has a buffer with storage size of $\mathcal{B}_i$, which saves the pre-loaded video data for vehicles $\mathcal{V} = \{V_1, V_2, \ldots, V_k, \ldots, V_K\}$ currently associated with mmWave base station $\mathcal{S}_i$. Both the whole buffer size $\mathcal{B}_i$ and the allocation of buffer space to each vehicle can affect the video streaming quality. The size of each buffer is assumed to be large enough to save the video data. The pre-loaded video data for vehicle V_k is saved in the allocated buffer space $\mathcal{B}_{i,k}$, then transmitted to the vehicle V_k through an mmWave channel to play. If vehicle V_k leaves the cell, its allocated buffer space $\mathcal{B}_{i,k}$ will be released. To achieve better video streaming quality, we propose a buffer space allocation mechanism to indicate the allocated buffer space $\mathcal{B}_{i,k}$ for vehicle V_k under buffer capacity constraint $\Sigma_{k=1}^{K}\mathcal{B}_{i,k} \le \mathcal{B}_i$. The available buffer space ($\mathcal{B}_i - \Sigma_{k=1}^{K}\mathcal{B}_{i,k}$) is the reserved space for newly entering vehicles in the case when no vehicles leave the cell before new vehicles enter the cell. The total duration $T_{i,k}$ that a vehicle V_k can stay in cell $\mathcal{C}_i$ can be estimated by cell size and the current vehicle speed. The allocated buffer space is $\eta T_{i,k}R_k$, where $0 \le \eta \le 1$ and R_k is the required data rate for video streaming of vehicle V_k. Larger allocated buffer space for a vehicle can provide better video streaming quality while occupying the buffer space, which could be used by other vehicles entering the cell in the future. Smaller allocated buffer space in the mmWave base station might not be sufficient for vehicles to maintain video streaming quality until the video data from the remote video server is transmitted to vehicles. η can be used to adjust the allocated buffer space for each vehicle in order to optimize video streaming quality of all the vehicles. Additionally, the coefficient η can be used to achieve fairness in buffer space allocation among vehicles. The buffer space allocation for each vehicle occurs when the vehicle enters the cell. The vehicle uses the allocated buffer space until it leaves the cell.

Buffer System at Each Vehicle

As discussed above, frequent link outages can occur in connections between vehicles and 5G base stations, which can lead to frequent freezing of video streaming at vehicles. To improve a vehicle's video streaming quality, a buffer system (Fig. 3b) is enabled in each vehicle and is connected to the mmWave channel to receive video data packets from base stations. The video data in the buffer is combined into frames and injected into the video player in vehicles. Video playout quality can be maintained for a specific period after mmWave link outage occurs, with the video data packets stored in the buffer. With intermittent mmWave connection, the buffer can be charged or discharged alternatively. Since mmWave communication has high transmission data rate (e.g., up to 10 Gb/s), the buffer can be mostly or fully charged with a short period of time when mmWave connection is available. Thus, with proper buffer size, the data saved in the buffer can mitigate the video frozenness.

In order to maintain video streaming for a specific period when mmWave link outage occurs, the bandwidth allocated to each vehicle to charge the buffer has to be larger than the packet departure rate from the buffer to the video player. Since many moving vehicles are dynamically associated with mmWave base stations, the dynamic bandwidth allocation among vehicles associated with each mmWave base station can significantly affect video streaming quality. In this article, we use a Markov decision process to formulate the bandwidth allocation problem. The state of the system is defined as the status indicating whether each vehicle is associated with each base station, for example, a $M \times K$ matrix with each element of 0 or 1. If a vehicle enters a new cell, the system transits to a new state, and the corresponding action for the new state is the allocated bandwidth for the vehicle entering the new cell. The objective of the Markov decision process is to achieve optimal video streaming quality for all the vehicles during the considered period under the capacity constraint of each base station. By solving the Markov decision process, there is an optimal bandwidth allocation for each state of the system. When the system starts to run, if a vehicle enters a new cell that corresponds to a new system state, the optimal bandwidth allocated to that vehicle can be determined immediately from the pre-calculated Markov decision process results. The total bandwidth allocated to all the vehicles associated with each base station should be less than or equal to the mmWave base station's capacity. Since vehicles have high speed and move among different small cells, the duration of each vehicle staying in a specific cell is relatively short. To simplify the bandwidth allocation mechanism, the bandwidth allocation to each vehicle occurs when it enters the cell, and it uses the allocated bandwidth to charge its buffer until it leaves the cell. The integrated double-buffer system combines the buffer system in the mmWave base station and the buffer system in mobile vehicles to mitigate the delay effect and intermittent connection effect on video streaming over 5G enabled vehicular networks.

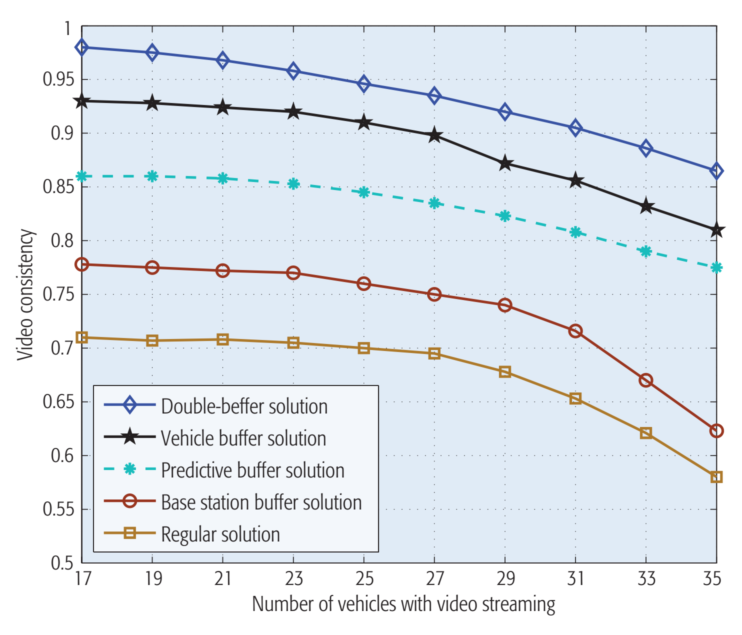

FIGURE 4. Video consistency in 5G enabled vehicular networks.

Performance of the Double-Buffer System

Video smoothness is the main performance aspect to demonstrate video streaming quality [7]. *Video consistency* is used to quantify video smoothness; it is the percentage of time when video streaming is smooth without freezing of the total video streaming duration of each vehicle. We consider a segment of highway covered by 180 mmWave base stations, each of which has data rate capacity of 15 Gb/s. A number of vehicles

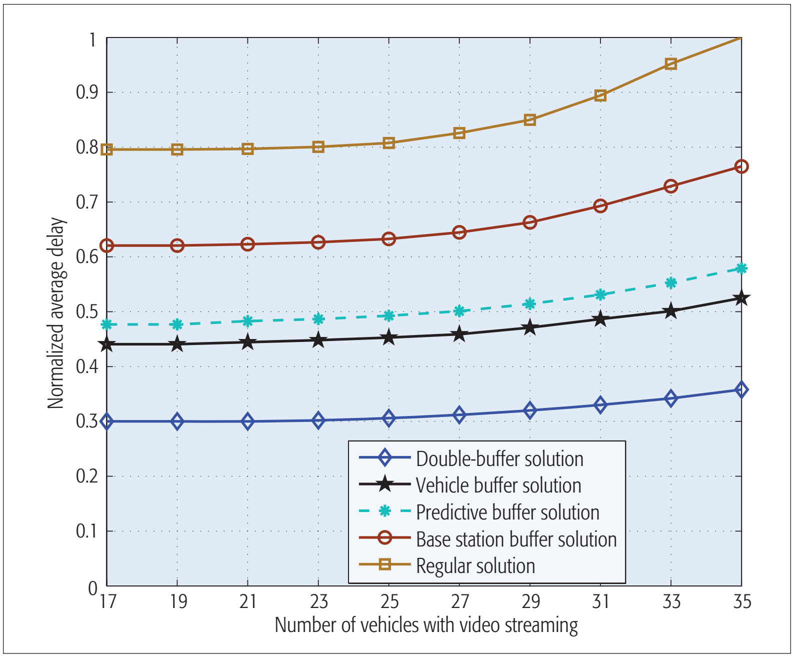

FIGURE 5. Delay of video streaming in 5G enabled vehicular networks.

move from the first few cells at the beginning of the considered highway section to the end of the considered highway section. They move into/out of different cells with handoffs. The time duration $T_{i,k}$ for each vehicle staying in cell C_i until it moves into the next cell C_{i+1}, uniformly distributed within [2 s, 4 s]. The directional communication duration in each cell is randomly selected in the range of [1 s, 2 s]. The buffer in each mmWave base station is 20 GB, while the buffer in each vehicle is 2 GB. The required data rate of uncompressed video streaming in each vehicle is randomly selected in the range of [0.8 Gb/s, 2 Gb/s].

Figure 4 shows the video consistency of various numbers of vehicles with video streaming. The base station buffer solution only installs buffer systems in 5G base stations, while the vehicle buffer solution only installs a buffer system in each vehicle. The regular solution does not install any buffer system. The predictive buffer solution adopts the buffer management mechanism in [14] to charge the buffer system in each vehicle. With the proposed buffer size allocation mechanism in the 5G base station and the bandwidth allocation scheme charging the buffer in each vehicle, the double-buffer solution can achieve much better video streaming quality compared to other solutions since it mitigates both the delay impact and the impact of intermittent connection. The vehicle buffer solution has better video consistency than the predictive buffer solution since it achieves optimal video consistency for all the vehicles in the network.

The average delay at the video player is shown in Fig. 5. The base station buffer solution can mitigate the delay from remote video server to mmWave base station, which results from directional handoffs and/or video data retransmission. The vehicle buffer solution can mitigate the impact of intermittent connection, which could result in delay by video data retransmission. Therefore, the double-buffer solution can significantly reduce the delay at the video player, which greatly improves the video streaming quality.

CONCLUSIONS AND FUTURE RESEARCH

In this article, we have discussed 5G technologies and the challenges for video streaming over 5G enabled vehicular networks. A double-buffer system is proposed to improve video streaming quality by eliminating the effect resulting from frequent handoffs of high-speed vehicles and the intermittent connection effect due to mmWave propagation features. The proposed double-buffer system with the corresponding buffer space allocation mechanism and bandwidth allocation mechanism can effectively improve video streaming quality for high-speed vehicles at the cost of buffer storage. The communication overheads and computation overheads brought by the proposed buffer space allocation mechanism and bandwidth allocation mechanism are not heavy since we do not implement complex mechanisms in this article.

Since buffer space allocation in mmWave base stations and the bandwidth allocation for vehicles associated with the same mmWave base station are strongly correlated, joint optimization could be applied to achieve optimal video streaming quality for all the vehicles in the networks. The results should be helpful in designing simplified mechanisms for buffer space allocation and bandwidth allocation. On the other hand, some bandwidth-intensive applications require real-time communication, such as haptic communication and interactive gaming over 5G enabled vehicular networks. For these applications, directional connectivity should be maintained always. One possible solution is to make both the transmitter and the receiver direct their beams toward each other by beam tracking when they are moving.

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