mmHandover: A Pre-Connection based Handover Protocol for 5G Millimeter Wave Vehicular Networks

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ABSTRACT

With the increase of data driven vehicular applications, existing networks cannot satisfy the communication requirements. Therefore, 5G millimeter wave (mmWave) communications, which can offer multi-gigabit data rate, hold potential to be utilized in vehicular networks. On one hand, due to the densely deployed 5G base stations, frequent handover will largely decrease the quality of service, where recent handover is at hundred-millisecond level. On the other hand, mmWave links are easily broken by obstacles because of short wavelength. Yet existing handover protocols do not consider the blockage problem, which frequently occurs in mmWave based networks. To address these problems, we propose a real-time handover protocol called mmHandover for 5G mmWave vehicular networks leveraging mmWave antennae. In mmHandover, multiple antennae in one array are divided into two parts: pre-connected antennae and data transmission antennae. In parallel, pre-connected antennae build the connection with multiple candidate base stations before activation based on a designed pre-connection strategy, while data transmission antennae are responsible for data delivery with the currently connected base station. When handover is triggered or blockage happens, one of the pre-connected links will convert into data transmission link, thus realizing almost seamless handover. Finally, real data-driven simulations demonstrate the efficiency and effectiveness of mmHandover. Compared with standard 4G/WiFi handover protocols, mmHandover greatly reduces the delay from more than 5000µs to about 1000µs. Besides, the delay gap will get widened coupled with increase in the number of vehicles.

KEYWORDS

5G Millimeter Wave, Pre-Connected Link, Vehicular Networks, Handover Protocol

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1 INTRODUCTION

The automobile industry has recently enjoyed a rapid development with regard to quality, reliability, and safety. A wide variety of bandwidth intensive applications (e.g., collision detection system, lane change warning, navigation) embedded in vehicles gain more and more popularity so as to enjoy travel safety, smart and green transportation, entertainment and so on. The global market of connected vehicles is increasing at a high speed and forecasted to reach USD 131.9 billion by 2019 [15]. Providing advanced wireless access to mobile vehicles is expected to be the next frontier for vehicles revolution [5]. Furthermore, since most of these applications are delay sensitive, high speed connectivity is essential for upcoming connected vehicular applications.

Two state-of-the-art wireless techniques are regarded as the most promising candidates in vehicle-to-infrastructure (V2I) networks: WiFi networks and cellular networks. Although WiFi based V2I networks seem more feasible and cost-effective to deliver Internet services, its performance is fundamentally restricted by high vehicle speeds and intermittent links [6]. For cellular networks, exponential growth of mobile data traffic has already put great pressure on them. Off-the-shelf cellular infrastructures can hardly deliver massive extra mobile traffic produced by a large number of vehicles [15].

To provide bandwidth-hungry services to vehicles, two critical factors should be taken into account. First, wireless links should offer at least an order of magnitude higher data rates than that of available wireless technologies. Second, intra-cell and inter-cell interference between nearby mobile vehicles should be minimized even when base stations are densely deployed. Therefore, mmWave communications are a promising candidate for V2I networks, which can support multi-Gbps data rates at a short distance. Interference among concurrent transmission links can be minimized by sharp formed beams. In addition, existing research demonstrates that the size of mmWave antenna array with 256 elements just accounts for 256cm^2 of area due to short wavelengths [7]. Large-scale mmWave antenna arrays can be easily integrated into small physical spaces. Then, mmWave links based on directional beams can drastically reduce interference from other base stations or vehicles [12]. Zhu et al. [25] demonstrated that highly directional links in 60GHz mmWave picocells can reach nearly 200m at high data rates.

To construct real-time mmWave vehicular networks, handover is fundamental and significant. Due to the dense deployment of 5G mmWave base stations and high vehicle speed, more frequent handover will occur in vehicular networks. However, existing handover protocols always bring a delay of several hundred milliseconds, decreasing the quality of service, especially for those delay-sensitive vehicular applications. In addition, mmWave links based on beams can be easily broken by obstacles. Nevertheless, existing handover protocols do not take the blockage problem into consideration [16]. Therefore, in this paper, we mainly focus on minimizing the delay when handover is triggered or blockage happens.

Standard handover protocols in LTE and WiFi follow the rule that "one period of time for data transmission, another period of time for connection". It means that dedicated time should be spent on connecting with new base stations when handover is triggered, which extends the service delivery time and compromise the quality of service. This is because all antennae embedded into terminals are used for data transmission [19]. Therefore, these conventional handover protocols are not suitable for satisfying the requirements of delay-sensitive applications in 5G mmWave vehicular networks.

There exist three challenges that should be conquered to achieve seamless handover in 5G mmWave vehicular networks. Firstly, large-scale mmWave antenna arrays should be utilized in an optimal way since more pre-connection antennae mean less transmission antennae, thus reducing the total throughput. Secondly, the pre-connection scheme should accomodate for different road conditions in metropolises. Thirdly, based on mmWave antenna arrays, how to ensure the reliability of mmWave links and realize seamless handover is a challenging problem owing to frequent handover.

To address these challenges, we propose a novel handover protocol named mmHandover specialized for mmWave vehicular networks. Leveraging large-scale mmWave antenna arrays, we divide them into data transmission antennae and pre-connection antennae. In parallel, partial antennae are utilized for pre-connection. The remaining antennae can be employed for data transmission with nearby base stations. In addition, we make a trade-off between the number of pre-connection antennae and the number of data transmission antennae based on total throughput and link robustness. Finally, we design a new pre-connection selection scheme to adjust for complex road conditions according to vehicles' travelling direction and location information. Accordingly, whenever handover or blockage happens, the currently connected base station named source base station only needs to send a handover request to the target base station to activate one pre-connection link, greatly simplifying the handover process. Extensive simulation results show that with increase in the number of vehicles, the handover delay in LTE networks increases from more than 5000µs to about 160400µs. However, mmHandover delay just increases from 1478µs to less than 4200µs.

The main contributions of this paper are summarized as follows.

- To the best of our knowledge, this is the first work to study the handover problem in **5G mmWave vehicular networks**.
- With acceptable total throughput loss, mmHandover fully exploits the mmWave antenna array through assigning partial antennae to build the pre-connection with candidate base stations. Then, seamless handover can be achieved, which is pretty important for delay-sensitive applications.
- Real trace based simulations are extensively conducted to evaluate the performance of mmHandover. Performance results demonstrate that mmHandover outperforms the standard WiFi and LTE handover protocols in terms of delay and throughout.

2 RELATED WORK

We discuss existing research about WiFi based handover protocols and cellular based handover protocols, respectively. Recent advances in mmWave studies will also be introduced.

WiFi based handover protocols. WiFi channels have been suggested to be the Internet access for V2I networks since millions of WiFi hotspots have been deployed all over the world. Wu et al. [23] and Teng et al. [21] showed that channel scan in the WiFi handover procedure is time-consuming. In [23], a fast handoff scheme named proactive scan can reduce delay through performing the operation of scan in advance. In [21], D-Scan is proposed to extract access point(AP) information from wireless traffic and then the active probing time can be significantly decreased. Yet, the accuracy of channel information is limited by the interval of probing.

Cellular based handover protocols. Cellular based access technology can also act as a reliable and ubiquitous Internet access for high speed vehicles. Jansen et al. [8] and Lobinger et al. [14] performed handover parameter optimization in LTE networks in order to improve the overall performance. In [13], an LTE femtocell-based network mobility scheme named MEN-NEMO for high-speed rail systems is proposed to achieve seamless handover. However, it cannot be applied to address our problem since it is under the condition of single traveling direction and does not consider the blockage problem.

Research on mmWave. As a promising wireless technology, mmWave communications have received extensive attention from industry and academia [9, 22]. Zhou et al. [24] design a novel wireless network structure named 3D beamforming for data centers, in which 60GHz signals can be reflected by data center ceilings. Hence, none-line-of-sight wireless links between any two racks can be established. In addition, the authors of [25] have dispelled some common myths. The feasibility of 60GHz mmWave picocells with regard to reflections, sensitivity to movement and blockage, and interference in typical urban environments has been investigated.

3 PROBLEM FORMULATION

In this part, the motivation of this paper will be introduced, as well as the problem formulation.

3.1 Motivation

Base stations are densely deployed in 5G mmWave networks [20], which implies that handover will occur more frequently, especially for high speed vehicles. Meanwhile, it is cost-effective to deploy large mmWave antenna arrays since they can be directly integrated with other portions of a transceiver and fabricated with either packaging or integrated circuit (IC) production technology. Hence, beamforming based on mmWave antenna arrays can be utilized to minimize the interference in densely vehicular network and extend the coverage range, which is completely different from WiFi and LTE networks. Therefore, existing LTE and WiFi handover protocols are not suitable in 5G vehicular networks.

In addition, it is predicted that applications related to security and autonomous driving will occupy more than half of vehicular application market by 2020, which is shown in Fig. 1. Nevertheless, these kinds of applications are highly sensitive to delay time. They have a strong desire for minimization of delay time between vehicles and base stations [17]. Therefore, with densely deployed base stations, handover delay between base stations and vehicles is a critical problem in 5G mmWave vehicular networks.

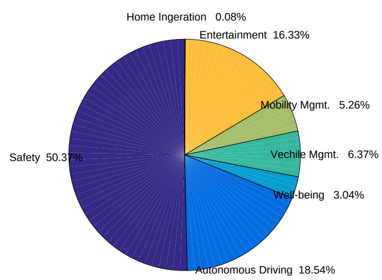


Figure 1: Market potential of vehicular applications.

3.2 Problem Statement

In this section, we target the handover problem. It consists of two sub-problems: (i) How to achieve seamless handover based on mmWave antenna arrays? (ii) How to handle the blockage problem in case of service interruption?

We assume that 5G mmWave base stations are deployed along the roadside, fully covering the road. Overlapped area exists between two adjacent base stations. mmWave base stations can support the data traffic delivery for vehicles even in relatively crowded environments. The handover procedure is completed through the X2 interface between two base stations. The system model of mmWave vehicular networks is shown in Fig. 2. The mobility management entity (MME) and serving gateway (S_GW) are responsible for vehicle mobility events and packet forwarding, respectively. A typical handover process is depicted as follows: Before a vehicle arrives at location 1, it has been attached to base station 1. When this vehicle arrives at location 1, the signal strength of base station 2 is higher than that of base station 1. Then, handover is triggered. Therefore, it needs to stop data delivery with base station 1, followed by an attempt to connect with base station 2. Normally, this operation will bring about hundreds of milliseconds delay, which in turn degrades the throughput performance. The objective of this paper is to **minimize the delay caused by handover procedure while ensuring the reliability of mmWave wireless links**.

Table 1: Notations

Notation	Meaning
$v_i \in V$	v_i: Vehicle i; V: The set of vehicles
$b_j \in B$	b_j: Base station j; B: The set of base stations
M	The number of antenna of mmWave antenna array
$L_{i,t}$	The position t of vehicle i when handover is triggered
$L_{i,t,c}$	The position c of vehicle i when handover is completed
L_i	The set of position of vehicle i when handover is triggered
$T_{i,t,total}$	Handover delay time when handover for vehicle i is triggered position $L_{i,t}$
$T_{i,t,tran}$	Information transmission time on wireless channels in the handover process when handover for vehicle i is triggered at position $L_{i,t}$
$T_{i,t,exe}$	Execution time in the handover process when handover for vehicle i is triggered at position $L_{i,t}$

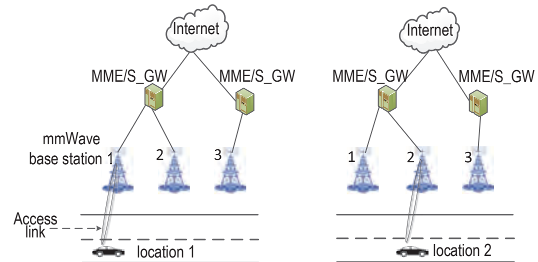


Figure 2: When a vehicle moves from location 1 to 2, the handover protocol moves the link from base station 1 to 2.

Table 1 demonstrates all the notations presented in the problem formulation. Suppose we have N vehicles denoted as $V = \{v_1, v_2, ..., v_N\}$. There are two situations that trigger handover: (i) Existing links between vehicles and base stations are broken by obstacles. (ii) The signal strength of a nearby base station is stronger than the currently connected base station. When vehicle i arrives at location $L_{i,t}$, handover for vehicle i is triggered. When vehicle i arrives at location $L_{i,t,c}$, vehicle i successfully switches to another base station. Then, handover process is accomplished. The consuming time during the handover process is described as $T_{i,t,total}$. According to the LTE handover procedure, the delay is composed of information transmission time on wireless channels $T_{i,t,tran}$ and execution time of all units $T_{i,t,exe}$. In particular, $T_{i,t,tran}$ is equal to the time consumption caused by handover information delivery among the vehicle, source base station and target base station. $T_{i,t,exe}$ is denoted as the time consumed by operation performed by base stations and the vehicle. Then, the following equation is established:

$T_{i,t,total} = T_{i,t,tran} + T_{i,t,exe}$. Based on mmWave antenna arrays, how can we realize seamless handover? the problem formulation can be expressed as follows.

$$\min \quad (T_{i,t,tran} + T_{i,t,exe}), \forall v_i \in V, \forall L_{i,t} \in L_i. \tag{1}$$

4 OVERVIEW OF MMHANDOVER

To tackle the problem, we propose mmHandover, a handover protocol tailored to 5G mmWave vehicular networks. It is based on the full use of mmWave antenna arrays. The antenna arrays can be employed in mobile vehicles to achieve data transmission with the currently connected base station and pre-connection with other candidate base stations simultaneously. When handover is triggered, the source base station should just send a handover request to inform the target base station to activate the pre-connected link. Accordingly, seamless handover process can be achieved. It is especially significant for delay-sensitive vehicular applications under the condition of frequent handover due to vehicles' high speed and relative distance between two mmWave base stations. Meanwhile, whenever the access links between base stations and vehicles are broken by obstacles, signal strength from the vehicle will drop rapidly at the source base station. Subsequently, the source base station will also send a request to activate one pre-connected link.

mmHandover protocol is designed based on the LTE handover protocol [4], facilitating the maximization of compatibility with 5G communication systems. Furthermore, based on the characteristics of mmWave, we have made corresponding improvements to meet the requirements of mmWave outdoor communications. The handover flowchart is shown in Fig. 3. Detailed steps are described as below:

(1) **Pre-connection**: A vehicle sends measurement beacons periodically. It will select n ($n \geq 1$) candidate base stations (except for the source base station) to preconnect according to the received signal strength and their locations. Then, it sends pre-connection requests to these n base stations.
(2) **Pre-connection**: To respond the pre-connection request, the base stations make judgements on whether pre-connected requests can be admitted based on the maintained information. If admitted, they send preconnected request ACKs back to the vehicle. Then, pre-connected links are established, but without data transmission.
(3) The source base station configures measurement control information to the vehicle, informing the vehicle to carry out measurements so as to assist the source base station in managing the mobility of the connection.
(4) The vehicle does measurements according to the frequency information of network configuration and reports to the source base station in accordance with the measurement report configuration.
(5) The source base station makes handover decision based on the results of vehicle measurements and their own maintained information.
(6) **mmHandover**: If handover is triggered, the source base station sends a handover request to the target base station in preparation for handover. The information consists of request for activating the pre-connected link, Synchronization Status (SN), target cell ID and so on. Especially, the delivery of the SN status aims to transmit uplink PDCP SN receiver status and downlink PDCP SN sender status, ensuring the sequential reception and integrity of data.
(7) **mmHandover**: To respond the handover request, the target base station judges whether the activation operation is allowed. If admitted, the target base station will allocate resources to the vehicle.
(8) **mmHandover**: The target base station activates the pre-connected link.
(9) **mmHandover**: The data transmission antennas detach from the source base station and convert into the pre-connection antennas for the next period of time.

Steps from 10) to 15) are similar to traditional LTE. From the protocol described above, we can see that when handover is triggered, the only thing needed to do is to send a handover request to the target base station so as to activate the pre-connected link, greatly simplifying the handover process. (i) The delay caused by mmHandover for vehicle i only consists of the transmission time of handover request $T_{i,t}$, the consuming time $T_{i,activate}$ caused by activation, and the transmission time $T_{i,tran}$ consumed by steps from 10) to 15). Obviously, the sum of $T_{i,t}$ and $T_{i,tran}$ is much smaller than $T_{i,t,tran}$ and $T_{i,activate}$ is smaller than $T_{i,t,exe}$. Therefore, mmHandover delay is reduced. Specifically, the sum of $T_{i,t}$, $T_{i,tran}$, and $T_{i,activate}$ is at a microsecond level, which is much less than the sum of $T_{i,t,tran}$ and $T_{i,t,exe}$. (ii) Compared to LTE handover protocol, mmHandover almost does not employ the data transmission antennae to exchange control information with the source and target base stations. In other words, these antennae are dedicated to data delivery with the source base station until the handover request is sent. (iii) The pre-connected antennae undertake the task of signal strength measurement (e.g., RSRQ) of nearby base stations so that the data transmission antennae can concentrate on data delivery. These mechanisms further reduce the delay and enhance the mmWave network throughput. Therefore, seamless handover can be realized, which is crucial for delay-sensitive applications.

5 KEY COMPONENTS OF MMHANDOVER

To implement mmHandover, there are four key components remained to be determined, including the partition criterion of mmWave antenna arrays, the pre-connection mechanism, and the pre-connection based handover.

5.1 Partition Criterion of Antenna Arrays

Since multiple mmWave antennae can be embedded in the vehicle due to short wavelengths, we divide these antennae into two parts: pre-connected and data transmission antennae. However, there is no existing research studying how to divide antennae for different uses. Therefore, a novel strategy is necessary, whose objective is to determine the number of

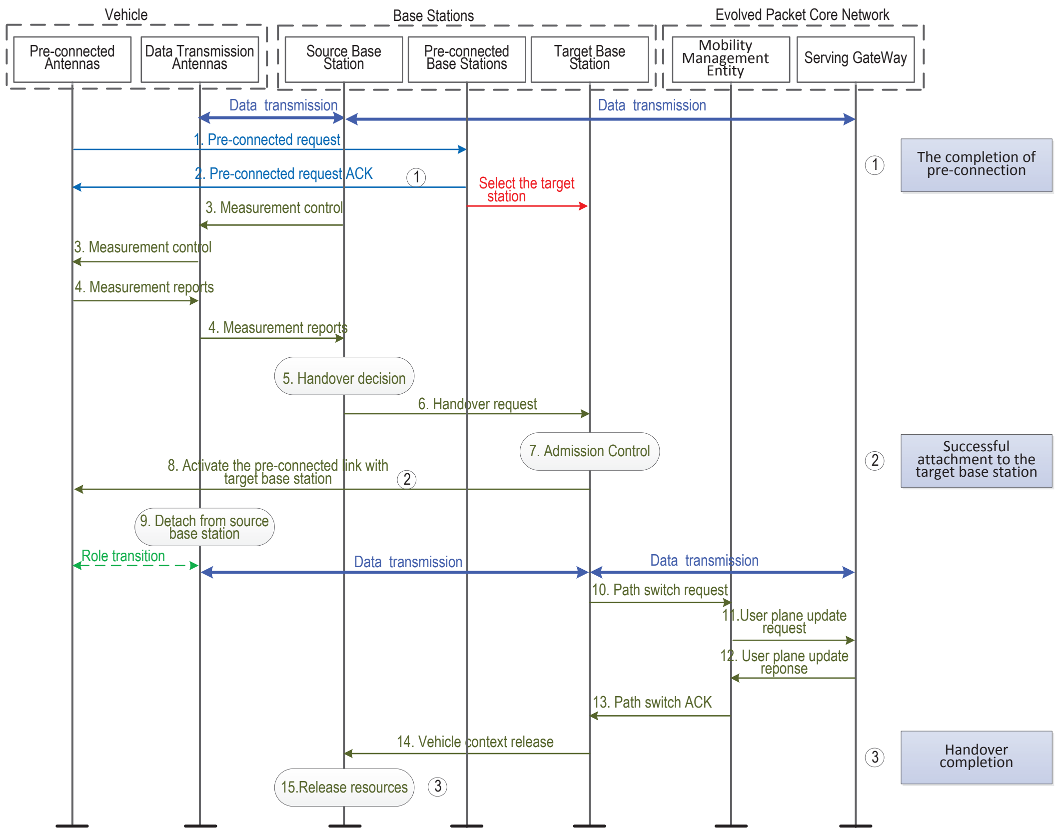


Figure 3: Flowchart for mmHandover.

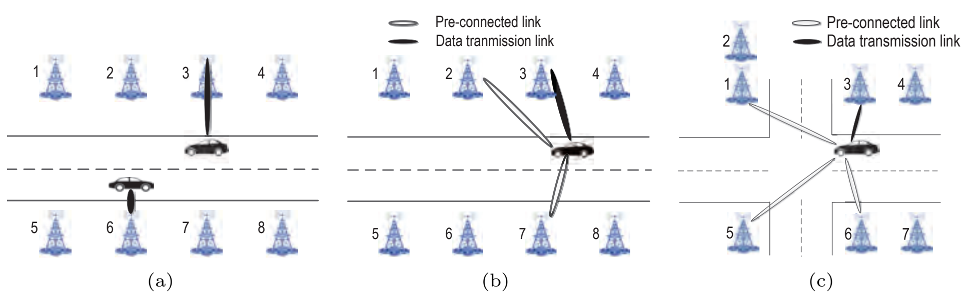


Figure 4: The sequence diagram.

antennae used for pre-connection first. The remainders are utilized for data transmission.

It is known that mmWave signals attenuate seriously in the air. Therefore, beamforming is utilized to transmit radio signals (electromagnetic waves) in a particular direction. Energy transfer rate can be significantly improved, which in turn extends the transmission range. As shown in Fig. 4(a), multiple antennae form the beam for data transmission with the currently connected base station. Suppose that m antennae are utilized for pre-connection. Each of them is a non directional point radiation source. The distance between two adjacent antennae is d. The amplitudes of each antennae are the same, which is denoted as E. The phase shifts of each phase shifter are 0, Φ, 2Φ,..., $(m-1)\Phi$, respectively. Φ is denoted as the current phase difference between adjacent antennae. The output field strength of each antenna is $\vec{E}_0$, $\vec{E}_1$, ..., $\vec{E}_{(m-1)}$. Θ is represented as the angle deviating from the normal. Then, assuming the antenna whose phase shift is 0 is set as the basis. The beamforming formula at the transmitters can be expressed as follows:

$$\vec{E}(\Theta) = \vec{E}_0 + \vec{E}_1 + ... + \vec{E}_i + ... + \vec{E}_{m-1} = \sum_{k=0}^{m-1} \vec{E}_k, \quad (2)$$

By unit conversion formula, we can get the dB value of field strength, which is expressed as follows:

$$E[dB] = 20\log_{10}|\vec{E}(\Theta)|, \quad (3)$$

Subsequently, according to the path loss model for outdoor mmWave channels in [18], the model is given by

$$PL(d)[dB] = PL(d_0)[dB] + 10n\log_{10}(\frac{d}{d_0}) + \chi_\sigma, \quad (4)$$

where,

$$PL[dB](d_0) = 20\log_{10}(\frac{4\pi d_0}{\lambda}), \quad (5)$$

d_0 is the free space reference distance in meters. n is denoted as path loss factor. χ_σ is the typical log-normal random variable with 0dB mean and standard deviation σ in dB for modeling the large-scale shadow fading. λ is the carrier wavelength. d is the separation distance between the vehicle and base station. $PL(d_0)[dB]$ is the path loss at reference distance. Therefore, through Equation (6).

$$SS[dB] = E[dB] - PL(d)[dB]. \quad (6)$$

The received signal strength SS at the base station can be obtained.

In this paper, we set the signal threshold as SS_{th}. If SS is higher than SS_{th}, the vehicle can transmit data to the base station. Therefore, based on the Equations (2)-(6), enough antennae should be provided to pre-connect with one base station. Then, the information from the vehicle can be delivered to the base station when pre-connection links are activated. Consequently, number of antennae for pre-connection and data transmission can be determined.

Pre-connection based mmHandover is optimal according to vehicular applications, especially for delay-sensitive vehicular applications. However, for applications which are not sensitive to delay time, such as entertainment, all antennae are utilized for parallel data transmissions based on MIMO beamforming. The utilization of pre-connection antennae will cut down the throughput to a certain extent. Therefore, the number of pre-connection links is limited to less than three. The remaining antennae are employed for data transmission. Simulation results in Section 6 will show that three pre-connection links are sufficient to guarantee the robustness of mmWave links. Specifically, in general circumstances we will set two pre-connection links. When at the crossroads, three pre-connection links will be established in parallel. Thus, the robustness of mmWave links can be ensured, and throughput loss is acceptable, which will be presented in Section 6. Meanwhile, interference among different beams can be minimized with a small number of pre-connection links.

5.2 Pre-Connection Selection

After determining the number of antennae for pre-connection, the remaining antennae are applied to deliver data traffic with roadside base stations. However, road conditions are complicated. Novel strategy for pre-connection should be

Algorithm 1: The pre-connected selection algorithm

input : M: the number of antennae; $m1, m2, m3$: the number of antennae for building three pre-connection links; B: the set of base stations; v_i: vehicle i; (x_i, y_i, z_i): the position of vehicle i

output : B_{pre}: the set of pre-connection base stations

$RoadType \leftarrow$ obtain the road type in which vehicle i is located based on (x_i, y_i, z_i);
$B_{pre} \leftarrow \emptyset$; $M_{rest} \leftarrow M$; $k \leftarrow 0$;
$v_{i,dir} \leftarrow$ the travelling direction of v_i;
$\overrightarrow{v_i b_j} \leftarrow$ the vector from v_i to b_j;
$Angle(v_i, b_j) \leftarrow \angle(v_{i.dir}, \overrightarrow{v_i b_j})$;
$B_0 \leftarrow \{b_j \mid Angle(v_i, b_j) \leq \pi/2 \& b_j \in B\}$;
if $RoadType$ *is straight* **then**
  if $k<2$ **then**
    while $M_{rest}>0$ **do**
      $j \leftarrow k+1$;
      $b_{str} \leftarrow \underset{SS[j]}{argmax}\{b_j \in B_0\}$;
      $B_0 \leftarrow B_0 \backslash b_{str}$;
      $d \leftarrow \left|\overrightarrow{v_i b_{str}}\right|$;
      $m_k \leftarrow$ calculate the number of antennae based on $\overrightarrow{v_i b_{str}}, d$ and Equations (2)-(6);
      $M_{rest} \leftarrow M_{rest} - m_k$;
      $B_{pre} \leftarrow B_{pre} \cup b_{str}$;
  else
    return B_{pre};
else
  if $k<3$ **then**
    if $k<2$ **then**
      while $M_{rest}>0$ **do**
        $k \leftarrow k+1$;
        $b_{str} \leftarrow \underset{SS[j]}{argmax}\{b_j \in B_0\}$;
        $B_{pre} \leftarrow B_{pre} \cup b_{str}$;
        $B_0 \leftarrow B_0 \backslash b_{str}$;
        $B \leftarrow B \backslash b_{str}$;
        $d \leftarrow \left|\overrightarrow{v_i b_{str}}\right|$;
        $m_k \leftarrow$ calculate the number of antennae based on $\overrightarrow{v_i b_{str}}, d$ and Equations (2)-(6);
        $M_{rest} \leftarrow M_{rest} - m_k$;
    else
      $b_{str} \leftarrow \underset{SS[j]}{argmax}\{b_j \in B_0\}$;
      $B_{pre} \leftarrow B_{pre} \cup b_{str}$;
      $B \leftarrow B \backslash b_{str}$;
      $m_k \leftarrow$ calculate the number of antennae based on $\overrightarrow{v_i b_{str}}, d$ and equations (2)-(6);
      $M_{rest} \leftarrow M_{rest} - m_k$;
  else
    return B_{pre};

proposed to adapt to road changes and reduce the number of pre-connection operations. Therefore, we will discuss the pre-connection mechanism in two different categories: straight roads and crossroads, as shown in Algorithm 1.

At the beginning, the algorithm determines the road type in which the vehicle is located. When on a straight road, the vehicle chooses two base stations to pre-connect based on the information about driving direction and locations of base stations. This is because too many antennae dedicated for pre-connection will reduce the number of data transmission antennae, thus compromising the total network throughput. Then, Algorithm 1 obtains the set of base stations in its driving direction, corresponding to steps from line 5 to line 8 in the algorithm. In these steps, it obtains the angles between the travelling direction of the vehicle and the vector from the vehicle to the base stations. Then, the base stations whose corresponding angels are smaller than $\pi/2$ belong to the set of base stations B_0 in the vehicle's direction. Secondly, according to Equations (2)-(6) in line 14, it computes the number of antennae, which can be used to pre-connect with the base station of strongest signal strength in the set B_0. After successful per-connection with the base station, this base station will be removed from the acquired set B_0 in line 12. Steps from line 10 to 16 will continue until the loop have been executed two times. Finally, the remaining $M-m_1-m_2$ antennae will be applied for data transmission based on MIMO beamforming. Fig. 4(b) takes 2 pre-connected links as an example. The vehicle will select m_1 antennae to pre-connect with base station 7, which is the station with the strongest signal strength in the driving direction of the vehicle. In the second selection process, m_2 antennae will be utilized to pre-connect with base station 2, which is the station with the strongest signal strength in the rest of base stations. Then, pre-connection process is completed. Subsequently, the remaining $M-m_1-m_2$ antennae are employed for building data transmission link with base station 3. This strategy can reduce the number of pre-connection, thus lowering down the network load.

When at the crossroad, different from the case on the straight road, the vehicle will select three base stations to pre-connect with so as to ensure that in every direction there exists one pre-connection base station. Firstly, it obtains the set of base stations B_0 in its driving direction. Then, it pre-connects with one base station, which is one with strongest signal strength in the set B_0. The process corresponds to steps from line 23 to line 29, and it will be repeated twice. Then, it selects the base station with the strongest signal strength to pre-connect with in the set B_0, which corresponds to steps from line 32 to line 35. Finally, remaining antennae, whose number equals to $M-m_1-m_2-m_3$, will be arranged for data delivery with the currently connected base station through MIMO beamforming. Fig. 4(c) demonstrates the situation at the crossroad, which takes 3 pre-connected links as an example. Based on the selection algorithm, the vehicle pre-connects with base station 1, then, with base station 5. Finally, it pre-connects with base station 6 even though base station 6 is in the opposite direction of its driving direction. This is because the signal strength from base station 6 is the strongest, in case of blockages when waiting for the traffic lights. Furthermore, This mechanism can guarantee that the target base station for handover belongs to the pre-connected base stations no matter what driving direction the vehicle chooses.

Therefore, the pre-connection selection algorithm can well address the challenge caused by complex road conditions. Pre-connection will be executed periodically. According to the experiment results in [2], 300ms of measurement update period is recommended for user equipment speeds of 3 to 120kmph. Hence, we set the pre-connection period to 300ms.

5.3 Pre-Connection based Handover

The pre-connected base stations and corresponding signal strength are sent to the source base station from the vehicle. Once the pre-connected base stations are updated, the pre-connection information will be re-sent to the currently connected base station. After successful pre-connection, one pre-connected link is informed to be activated by source base station whenever handover happens.

Next, we discuss the blockage problem because mmWave links are easily broken by obstacles, especially on crowded roads with many buses. According to the results in [25], if a user cannot communicate with its connected base station due to obstacle, one nearby base station can be informed to continue data transmission with the user. This collaboration mechanism can greatly improve mmWave link connectivity compared to only one base station. As shown in Fig. 5, the mmWave link between a vehicle and its connected base station is broken down by a bus. Hence, the received signal strength at the base station decreases rapidly, which is less than SS_{th}. Then, the connected base station sends a handover request to the target base station so as to activate the pre-connected link.

As mentioned above, the vehicle has pre-connected with a set of base stations, which improves the robustness of mmWave links. For example, when the pre-connected link with the strongest measured signal strength has been broken down by an obstacle when handover is triggered, other pre-connected wireless links can be activated instead.

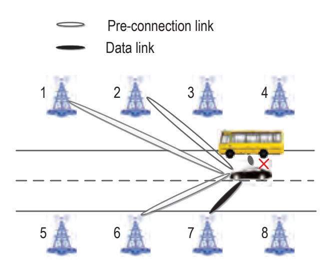


Figure 5: The blockage scenario.

6 PERFORMANCE EVALUATION

Extensive simulations are carried out to verify the high efficiency of mmHandover. Firstly, simulation settings are introduced. Subsequently, simulations are conducted according to the vehicle trajectory randomly generated by SUMO. Finally, we simulate the real vehicle trajectory in Shanghai. In SUMO based simulation, we can obtain handover delay in the case of different vehicles and analyze the relationship between the delay and the number of vehicles. Real trajectory based

Table 2: Probability evaluation

Settings		Number of pre-connected link		
Total number of vehicles	Number of buses	1	2	3
64	1	96.1%	100%	100%
64	2	95.3%	100%	100%
64	4	93.2%	99.4%	100%
64	8	90.6%	99.1%	100%
64	16	88.1%	94.5%	99.6%
64	32	80.3%	89.5%	99.1%

simulation aims to test the performance of mmHandover in actual situation.

6.1 Simulation Settings

The simulations are developed by NS3, which is one of the most widely used network emulators. We use SUMO [10] to generate vehicle trajectories. SUMO is a microscopic, multi-modal, and continuous road traffic simulation software. mmWave antenna arrays consist of 100 antennae, which can be implemented on the top of vehicles. We compare mmHandover with two existing handover protocols. One is the standard handover protocol in LTE networks. The other one is the handover protocol in WiFi networks. Base stations are evenly distributed along the road side. In LTE simulation, the distance between two adjacent base stations is 500m, which is the common deployment distance of base station in cities. In the simulation for WiFi and 5G mmWave communications, the distance between two adjacent base stations is set to 300m [25]. The data rates in LTE networks and in WiFi networks are set to 50Mbps and 54Mbps, respectively [3, 11]. According to the experimental results in [25], we set the data rate in mmWave networks to 385Mbps.

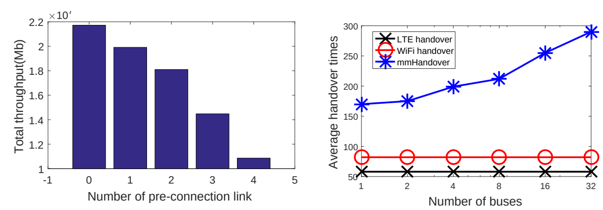
The delay is defined as the time taken from the handover decision to the completion of successful attachment to target base station. In this section, we mainly compare the handover delay and network throughput of these three protocols. In addition, we obtain and compare the handover times.

6.2 Arbitrary Trajectory based Simulation

In LTE networks, 6 base stations are set on both sides of the roads. For WiFi and 5G mmWave networks, we set up 10 base stations. Hence, a 1.5 kilometer long road can be completely covered, which is one-way with four lanes. All the vehicles start from the left of the road. Three traffic lights intersections are set up. Therefore, simulations can be carried out under the traffic scenes of different density and driving speed. We will set different cases by the total vehicle number of 1, 2, 4, 8, 16, 32, 64, 128, respectively. The duration is set to 200s. Based on SUMO, we can acquire arbitrary trajectories for each case.

First of all, the probability of target base station belonging to the set of pre-connected base stations is demonstrated in Table 2. It can be observed that when the number of buses remains the same, with the increase in the number of pre-connected base stations, the probability is increasing. Even if there are 32 buses, the probability is still over 99% when setting 3 pre-connected wireless links.

Next, the influence of number of pre-connection antennae on total throughput will be evaluated. For beamforming, the longer distance between the base station and vehicle means that more antennae are necessary to form the beam, thus reaching the base stations. Fig. 6(a) demonstrates the throughput degradation when the number of vehicles is set to 64. It can be observed that the total throughput declines when the number of pre-connection links increases. Meanwhile, the descent rate will speed up when the number of pre-connection links becomes larger. When the number of pre-connection links is set to 2, compared to 0 pre-connection link, the percentage of throughput decline is about 20%. This throughput drop is acceptable due to two reasons: (i) mmWave based networks can satisfy the requirements of majority of vehicular applications despite of certain throughput loss. (ii) Based on pre-connection, mmHandover can substantially shorten the handover delay, which is particularly critical for those highly delay-sensitive vehicular applications.

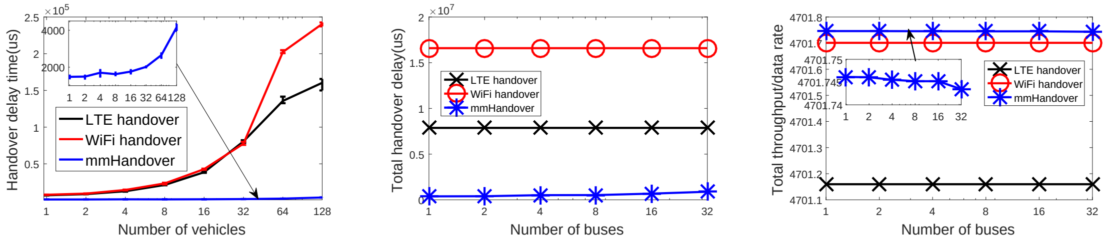


(a) (b)

Figure 6: Simulation results.

The comparison of handover delay of these three protocols is shown in Fig. 7(a). With the increasing number of vehicles, the delay of these three protocols is increasing. This is because more vehicles compete for limited resources, thus prolonging the delay. For LTE handover protocol, when the number of vehicles increases from 1 to 128, the delay time increases from about 5300µs to more than 160000µs. The delay time in WiFi networks ranges from nearly 8000µs to 240604µs. However, mmHandover delay only increases by a few microseconds, which is much less than the other two protocols. The main reason is that when handover is triggered, the only operation for mmHandover is to active the pre-connected link. Meanwhile, the delay in WiFi networks is longer than that of LTE handover protocol. In WiFi networks, more base stations are deployed than in LTE. More frequent handover will occur during the same period, resulting in more intense resource competition. Accordingly, the delay time is extended.

Next, 64 vehicles are set up, which consist of cars and buses. If one bus is located on the path between one car and its connected base station, the wireless link is broken down. Figure 6(b) shows the total handover times of LTE handover, WiFi handover, and mmHandover. We explore the simulation results of mmHandover in the case of different buses, which ranges from 1 to 32. We can observe that with the increase in the number of buses, handover occurs more frequently in mmHandover while the handover times in LTE and WiFi remains the same.



(a) (b) (c)

Figure 7: Simulation results based on arbitrary vehicle trajectory.

Table 3: Number of vehicles and buses

Date	Number of vehicles	Number of buses
Monday	152	6
Tuesday	163	5
Wednesday	162	2
Thursday	159	5
Friday	170	5
Saturday	133	9
Sunday	106	3

Next, we compare the total delay caused by LTE handover, WiFi handover, and mmHandover in the case of different number of buses. Simulation results are shown in Fig. 7(b). As depicted in Fig. 6(b), handover times will increase with the number of buses. Therefore, the total delay time caused by mmHandover is also increasing, yet the increasement is almost negligible. Meanwhile, although handover times in mmHandover are more than those of LTE and WiFi networks, mmHandover based total delay time is still much shorter than total delay time of two other handover protocols. This is because that much less delay time is consumed in mmHandover.

Figure 7(c) shows the ratio between the throughput and the set transmission rate during the simulation period. The ratio in mmHandover based network is a little bigger than the ratios in LTE and WiFi networks. The reason is that delay caused by mmHandover is much shorter than that of LTE handover protocol. With the increase in the number of buses, there will be a certain degree of decline in mmHandover based ratio. This is because more handovers will contribute to more handover delay time. However, it is still bigger than those of two other handover protocols due to its much shorter handover delay. Thus, a conclusion can be obtained: mmHandover based network capacity can be further enhanced despite that more handovers will happen.

6.3 Real Trajectory based Simulation

Real trajectory based simulations are conducted using traffic data of five minutes from 8 a.m. to 9 a.m. within a week in Shanghai [1]. We choose 8 a.m. to 9 a.m. because this period is the rush hour. The number of vehicles and the number of buses are shown in Table 3, coupled with 44 base stations in LTE networks and 76 base stations in WiFi networks and mmWave networks, respectively.

The delay of the three protocols is shown in Fig. 8(a). It is observed that the delay of mmHandover is much shorter than that of two other protocols from Monday to Sunday. This is because mmHandover cuts down the handover delay significantly based on the pre-connection mechanism. Then, the blockage period are not taken into account since it is at least 100ms level in conventional scenarios, while mmHandover just brings a few milliseconds of delay. Consequently, it is cost-effective to trigger handover whenever blockages happen.

Figure 8(b) demonstrates the total handover delay of the three protocols. Obviously, the total handover delay caused by mmHandover are mcuh less than two other protocols during the simulation although more handover times will occur in mmHandover based networks. This is because mmHandover based delay is much less than handover delay in LTE and WiFi networks, especially in crowded environments.

Figure 9 demonstrates the total handover times of the three protocols. Obviously, the handover times of mmHandover are more than two other protocols since blockage in mmWave vehicular networks may trigger handover.

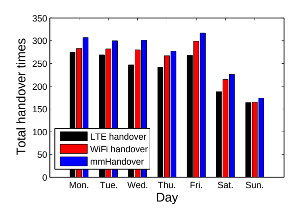
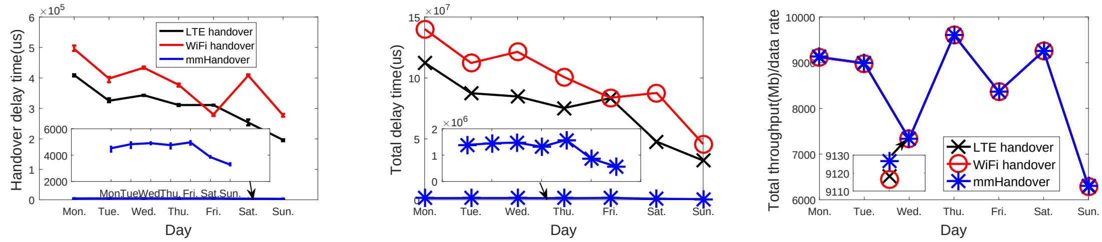


Figure 9: Handover times based on real vehicle trajectory.

Finally, we compare the throughput based on these three handover protocols. The results related to the ratio between total throughput and data rate are shown in Fig. 8(c). The ratio of mmHandover is always bigger than those of two other protocols from Monday to Sunday. This is because much less handover delay will be consumed in mmHandover based networks despite of more frequent handover compared to two other handover protocols. This kind of reduced time overhead can contribute to the increase in the total network throughput. Thus, mmHandover based network capacity can be further enhanced.

Through massive simulations based on vehicle trajectories generated by SUMO and real vehicle trajectory, it is verified that mmHandover outperforms LTE handover protocol and



(a) (b) (c)

Figure 8: Simulation results based on real vehicle trajectory.

WiFi handover protocol with regard to handover delay and throughput.

7 CONCLUSION

We have designed a pre-connection based handover protocol to build a real-time 5G mmWave vehicular network system. mmWave antennas are divided into two parts. One part is responsible for data transmission with source base station while the other part is utilized to pre-connect with nearby base stations. When handover happens, the target base station just should be informed to activate the pre-connected link, greatly shortening handover delay. Meanwhile, whenever the wireless link between source base station and vehicle is broken by obstacles, the pre-connected link will also be activated in order to improve the connectivity of mmWave links. Through extensive simulations, it is demonstrated that mmHandover has a superior performance compared to two other protocols, especially in handover delay.

8 ACKNOWLEDGMENTS

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