Millimeter-Wave Wireless Communications for IoT-Cloud Supported Autonomous Vehicles: Overview, Design, and Challenges

Linghe Kong, Muhammad Khurram Khan, Fan Wu, Guihai Chen, and Peng Zeng

The authors explore the capability of millimeter-wave communications for autonomous vehicles. As the next-generation wireless technology, mmWave is advanced in its multi-gigabit transmittability and beamforming technique. Based on these features, the authors propose the novel design of a vehicular mmWave system combining the advantages of the Internet of Things and cloud computing.

ABSTRACT

Autonomous vehicles are a rising technology in the near future to provide a safe and efficient transportation experience. Vehicular communication systems are indispensable components in autonomous vehicles to share road conditions in a wireless manner. With the exponential increase of traffic data, conventional wireless technologies preliminarily show their incompetence because of limited bandwidth. This article explores the capability of millimeter-wave communications for autonomous vehicles. As the next-generation wireless technology, mmWave is advanced in its multi-gigabit transmittability and beamforming technique. Based on these features, we propose the novel design of a vehicular mmWave system combining the advantages of the Internet of Things and cloud computing. This mmWave system supports vehicles sharing multi-gigabit data about the surrounding environment and recognizing objects via the cloud in real time. Therefore, autonomous vehicles are able to determine the optimal driving strategy instantaneously.

INTRODUCTION

An automotive revolution is taking place in autonomous vehicles. Without human intervention, autonomous vehicles [1] have the potential to remove more than 85 percent of traffic accidents caused by human errors. Moreover, drivers could get rid of boring tasks and enjoy their travels. Due to these benefits, "57 percent of consumers, globally, trust driverless cars — even more so in emerging markets" was reported in Cisco's survey. To meet market demands, automobile manufacturers have contributed great efforts. Several semi-autonomous technologies have been applied in practice such as Cadillac's super cruise and Benz's park assist. Furthermore, 53 Google driverless cars are self-driving in California and Texas for field tests.

The technology of autonomous vehicles is a typical convergence of the Internet of things (IoT) [2] and cloud computing [3]. From the macro aspect, navigation relies on GPS, map service, and road conditions, which is provided by cloud computing. From the micro aspect, an autonomous vehicle determines its real-time moving strategy depending on the dynamic surroundings. Many in-vehicle sensors make driverless cars go, but few are more important than the light detection and ranging (LiDAR) devices mounted on the roofs of vehicles. The LiDAR device scans more than 70 m in all directions, generating a precise three-dimensional map of a car's surroundings.

However, LiDAR, even with other sensors, is inadequate to ensure safe and efficient self-driving. In February 2016, a Google driverless car was at fault in a crash. Before that, LiDAR-based Google cars were involved in 17 minor accidents in six-year 2-million-mile tests. The possible problems are first, LiDAR is constrained by line of sight and cannot see through a large obstacle such as a truck ahead. Second, LiDAR performs poorly in bad weather. Third, LiDAR may incorrectly recognize some harmless objects (e.g., plastic bags) as obstacles. Fourth, LiDAR cannot discern human signs.

Vehicular communication systems [4] are a feasible solution to compensate for the drawbacks of LiDAR/sensors. Through two wireless modes, vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) [5], autonomous vehicles can acquire more traffic data to optimize their driving strategy. Existing works attempt to integrate commercial WiFi, Bluetooth, ZigBee, WiMax, and fourth generation (4G) into vehicles. In addition, the U.S. Department of Transportation has committed to use IEEE 802.11p-based dedicated short-range communications (DSRC) [6] on new light-duty vehicles beginning in 2017. Nevertheless, these conventional wireless communications have limited bandwidth. For example, the maximal bit rate of DSRC is 27 Mb/s. On the contrary, the traffic data are ever growing, such as LiDAR's 3D imaging and a camera's high-definition (HD) video.

The next-generation wireless technology, millimeter-wave (mmWave) [7], shows its potential to solve this dilemma. The much anticipated mmWave particularly works at 3–300 GHz [8], in which the available channel bandwidth is up to several gigahertz. Hence, mmWave can achieve multi-gigabit transmittability [9] for big data delivery. Moreover, mmWave exploits smart antenna arrays to realize the beamforming technique [10]. As a result, the constructive directional signal can track [11] and transmit to high-speed targets over

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Linghe Kong, Fan Wu, and Guihai Chen are with Shanghai Jiao Tong University; Muhammad Khurram Khan is with King Saud University; Peng Zeng is with the Chinese Academy of Sciences.

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	DSRC	WiFi	Bluetooth	ZigBee	WiMax and 4G	
Spectrum	5.9 GHz	2.4/5.8 GHz	2.4 GHz	868 MHz/915 MHz/2.4 GHz	2–6 GHz	1880–2650 MHz
Standard	802.11p	802.11a/b/g/n	802.15.1	802.15.4	802.16e	LTE
Bandwidth	10 Mb/s	20, 40 MHz	1 MHz	2 MHz	1.75–20 MHz	20 MHz
Bit rate	3–27 Mb/s	6–600 Mb/s	1–24 Mb/s	250 kb/s	Peak upload: 56 Mb/s, Peak download: 128 Mb/s	Upstream: 75 Mb/s, Downstream: 300 Mb/s
Modulation	OFDM	MIMO, OFDM	FHSS, GFSK, π/4-DPSK, 8-DPSK	DSSS, O-QPSK	OFDMA, MIMO	OFDMA, MIMO
Tx range	< 300 m	< 100 m	< 100 m	< 100 m	< 10 km	< 2 km
Cost	Cheap	Cheap	Cheap	Cheap	Expensive	Expensive

Table 1. Comparison of vehicular communication systems.

a long distance. These features exactly fit the demand of autonomous vehicles.

To fully exploit mmWave, we propose a novel vehicular mmWave system for autonomous vehicles. This system consists of both V2V and V2I mmWave communications. The V2V part enables the real-time exchange of sensory data (e.g., LiDAR data and HD video) among vehicles, helping to cover the blind areas and share vision in bad weather. The V2I part leverages the roadside infrastructure and cloud computing to feed back recognized objects and signs. Combining the multi-modal data, autonomous vehicles are able to immediately determine the optimal driving strategy. In this article, we introduce the framework design of a vehicular mmWave system and discuss the key design problems. Prototype and performance evaluation are conducted to demonstrate the feasibility of vehicular mmWave. The open issues and future directions are summarized at the end.

The proposed system is a general framework. It is easy to add customized components according to the demands of autonomous vehicles. We believe vehicular mmWave has wider implications and prospects for intelligent transportation applications than explored in this article.

RECENT ADVANCES IN AUTONOMOUS VEHICLES

An autonomous vehicle [1] (driverless car, self-driving car, robotic car) is a vehicle that is capable of sensing its environment and navigating without human input. To realize self-driving, autonomous vehicles first detect their surroundings by vehicle-mounted sensors. Then advanced control systems interpret sensory information to identify appropriate navigation paths as well as obstacles. To increase the sensing accuracy, an autonomous vehicle is equipped with at least two independent systems: the sensor system as the main part and the communication system as the assistant.

VEHICULAR SENSOR SYSTEMS

A vehicular sensor system is usually composed of LiDAR, radar, GPS, odometry, and computer vision [1]. In these sensors, LiDAR is considered as the "eyes" of recent driverless cars. The commercial LiDAR employing 64 laser diodes to produce 2.8 million data points per second with a 360° horizontal field of view and a 26.8° vertical field of view. By virtue of LiDAR, vehicles can detect obstacles and build 3D surroundings for safe navigation in dynamic environments. The effectiveness of LiDAR has been demonstrated in practice. But the other sensors are still indispensable, and play important roles in special applications such as side cameras for lane-keeping, infrared sensors for night detection, and sonar for distance measurement.

Nevertheless, the vehicular sensor system alone is not sufficient for a vehicle's automatic cruise. First, blind areas exist in LiDAR as well as other sensors because of the line-of-sight constraint (e.g., a vehicle cannot see through the vehicle ahead, causing overtake difficulty and potential risk). Second, sensors perform poorly in bad weather. The sensing range of LiDAR is largely reduced in heavy rain or snow. Third, it is not easy to identify whether a small object is harmless or not; for example, a wrong estimation of a plastic bag or a small mound may lead to needless veering, decreasing driving efficiency. Fourth, LiDAR is able to detect a human but isnot accurate enough to recognize human gestures; for example, it is difficult for sensors to distinguish the police gestures of "Go" and "Stop."

VEHICULAR COMMUNICATION SYSTEMS

In order to compensate for the drawbacks of sensor systems, a communication system is applied in vehicles [4]. Through wireless data sharing, a communication system is advanced in breaking the line-of-sight constraint and acquiring more data on surroundings, such as blind area information, even in bad weather. With more data, the vehicle can further optimize the driving strategy.

In the literature, scientists and engineers have attempted to implement various wireless standards into vehicular communication systems [5, 12]. A comparison of these standards is provided in Table 1.

Both DSRC and WiFi belong to the IEEE 802.11 family, the most common wireless protocol stack. The 802.11p-based DSRC [6] is specially designed for vehicular communications, which is close to 802.11a. The major difference is that the channel bandwidth of 11p is half that of 11a, so 11p's bit rate is half as much and the transmission range is three times longer than 11a. In addition, with multiple-input multiple-output (MIMO), the bit rate of 802.11n is up to 600 Mb/s.

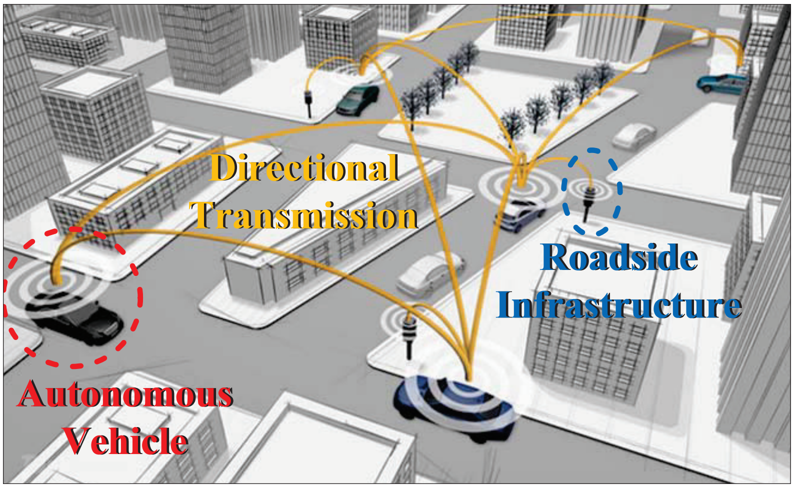

Figure 1. The vehicular mmWave system enables multi-gigabit transmission for V2V and V2I communication modes.

Parameters	Values
Spectrum	57–64 GHz
Number of channels	4
Bandwidth	2.16 GHz
Bit rate	693 Mb/s–6.76 Gb/s
Modulation	OFDM
Tx range	< 10 m (omni-antenna)
Cost	Cheap

Table 2. Key parameters of IEEE 802.11ad for 60 GHz mmWave communications.

The advantage of Bluetooth and ZigBee is low power, where the power consumption of Bluetooth 4.0 is as low as 0.5 mW. However, these low-power standards adopt simple modulation techniques, leading to a low bit rate, where the bit rate of Bluetooth Low Energy (BLE) mode is 1 Mb/s and that of ZigBee is only 250 kb/s.

WiMax and 4G LTE are base station driven long-distance transmission technologies widely adopted in cellular networks. They can provide megabit wireless access service even in a high-speed mobile environment. However, the base stations are expensive, and vehicular users need to pay for the data traffic during their driving.

Although there are numerous standards for vehicular communication systems, none of them is qualified for autonomous vehicles. The common problem of existing standards is that their transmittability is limited at the megabit level. In contrast, LiDAR and HD cameras in autonomous vehicles generate huge amounts of data every second. Sharing these data among multiple vehicles, especially in a crowded scenario, urgently requires gigabit wireless transmission.

Millimeter-Wave Wireless Communications

The next-generation mobile technology, mmWave [7], is envisioned to offer multi-gigabit wireless service for emerging applications [13]. Before applying mmWave to autonomous vehicles, we first introduce the promises and propagation characteristics of mmWave.

The first promise of mmWave is bandwidth. Take 60 GHz as an example. The unlicensed 60 GHz band provides 7 GHz bandwidth for mobile applications and is supported by IEEE 802.11ad, targeting indoor multi-gigabit wireless networks. Benefiting from the wide bandwidth, the bit rate of 802.11ad is up to 6.76 Gb/s [9]. TP-Link announced the world's first 802.11ad router in January 2016; the peak bit rate achieved is 7 Gb/s. The other key parameters in 802.11ad are listed in Table 2. If we transplant such multi-gigabit transmittability into autonomous vehicles, sensory data including LiDAR's 3D images and cameras' HD videos can be shared among all neighboring vehicles in real time.

Besides the bandwidth, another promise is short wavelength. Since the wavelength of mmWave is at the millimeter level, it is possible to pack a large number of antennas into small space (e.g., a 100-element 60 GHz array can be integrated into 1 in^2. Thus, the beamforming technique is handily applied in mmWave. Beamforming [10] is a signal processing technique to generate directional signal transmission by smart antenna array. Although the transmission range of mmWave is only 10 m in omnidirectional broadcast mode, beamforming can concentrate power in one direction and offer a transmission range that exceeds 130 m for 385 Mb/s and 79 m for 2 Gb/s. Beamforming is significantly helpful for autonomous vehicles. On one hand, the directional transmission assists the localization in the high-speed mobile environment. On the other hand, beamforming realizes concurrent transmissions by space-division multiple access (SDMA) and reduces the interference.

Moreover, mmWave has significantly different propagation characteristics compared to the 2.4/5.9 GHz band, where WiFi, Bluetooth, ZigBee, and DSRC operate:

Propagation: In free space, the signal strength is mainly lost due to oxygen absorption, where the loss of 60 GHz mmWave is about 16 dB/km [14]. Although it is difficult to realize a long-range (kilometer-level) link, mmWave has little effect within a short range because beamforming enhances the spatial reuse. For example, the loss due to oxygen absorption and heavy rain at 50 mm/hour is 36 dB/km, which works out to a modest 3.6 dB for a transmission range of 100 m.

Penetration: While 2.4/5.9 GHz signals penetrate through some objects, mmWave signals are easily blocked by most solid materials. Even a human body will introduce 20–50 dB of loss. In addition, since the transmission power is limited to 40 dBm by the Federal Communications Commission (FCC), mmWave does not have adequate power to burn through obstacles [8]. Therefore, it is challenging to guarantee robust mmWave connectivity in dynamic and obstacle-rich transportation environments.

Doppler: The Doppler effect depends on frequency and mobility. If the mmWave frequency is 3–60 GHz with mobility speed within 3–350 km/h, the Doppler shift will range from 10 Hz to 20 kHz. Due to the concentrated beam, there is a non-zero bias in the Doppler spectrum, which is largely compensated by automatic frequency control (AFC) [7] at the receiver side. As a result, the Doppler effect of mmWave can be well solved in vehicular communication systems.

DESIGN OF VEHICULAR MMWAVE SYSTEMS

To satisfy the big data delivery in autonomous vehicles, we propose a novel vehicular mmWave system. The ideal vehicular mmWave system operates as shown in Fig. 1, where any vehicle directionally connects with other vehicles and roadside infrastructure. The proposed system has three principal members:

1. Every *autonomous vehicle* is equipped with an mmWave radio, LiDAR, a camera, and the other usual sensors.
2. The *roadside infrastructure* consists of an HD camera and an mmWave radio. In addition, the infrastructure has a wired connection with the cloud.
3. *Cloud computing* has strong computational capability for data analyzing and path planning.

The framework of the vehicular mmWave system is shown in Fig. 2. This framework provides services based on V2V and V2I communication modes.

V2V mmWave communication: With mmWave radios, vehicles are able to share real-time sensory data within transmission ranges, forming an IoT application. Thus, the blind area and bad weather problems are effectively addressed. In detail, when a vehicle observes a blind area in its sensing range, it asks for LiDAR or camera data from neighboring vehicles to compensate. In addition, although the LiDAR's sensing range is sharply reduced in bad weather, mmWave's transmission range has almost no influence. Leveraging the shared sensory data, a vehicle can reconstruct the 3D road conditions by multi-source multi-modal data analysis [15].

V2I mmWave communication: In this mode, the roadside infrastructure works as a relay to forward data between vehicles and the cloud. Therefore, the recognition problems can be tackled well. For example, when a vehicle senses but cannot identify an object or a human gesture, it transmits HD video to the cloud. Benefiting from big data and strong computation capability, the cloud is able to accomplish the recognition instantaneously and feed the result back.

Above all, the vehicular mmWave system is helpful to autonomous vehicles for safe and efficient driving. The main contribution is that mmWave changes the self-driving strategy from purely local control to collaborative control. However, the proposed system cannot work with only the abstract framework. Next, we discuss four key design problems and their potential solutions for this system.

DATA PRIORITY

The objective of data priority is to determine which sensory data can be transmitted in advance when wireless collision occurs. We classify the communication needs into three priorities.

Priority I: Emergent data. Safety is the first criterion in autonomous vehicles. When a vehicle detects or estimates any dangerous surroundings such as a car crash, its highest priority is to immediately transmit these data to neighboring vehicles and infrastructures.

Priority II: Application-driven request. The communication needs are triggered by vehicular applications. For example, when an autonomous vehicle plans to overtake a truck ahead and cannot sense the road conditions in front of the truck, this vehicle sends a request to the truck. Then the truck responds its LiDAR's and HD camera's data. The priority of the application-driven request is second only to the emergent data.

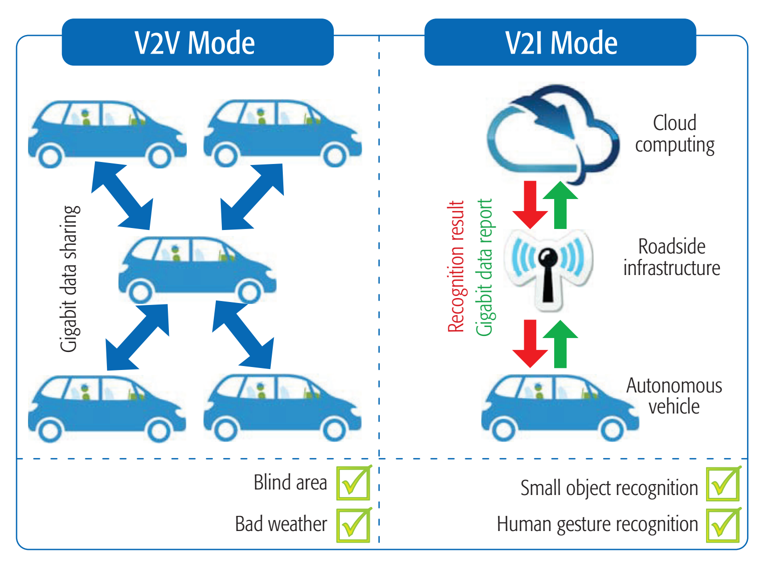

Figure 2. The framework of vehicular mmWave system.

Priority III: Routine broadcast. When the mmWave channel is not occupied, routine messages are broadcast to all single-hop neighbors including vehicles and infrastructures. Routine messages can include GPS information, movement information, mmWave's channel state, and abstracted sensory data. Moreover, a vehicle transmits data every time it traverses an intersection.

In mmWave's medium access control (MAC) layer, we set data with the highest priority having the shortest backoff range, which can be sent first after collision. Similarly, data with the lowest priority has the longest backoff range.

DEPLOYMENT PLAN

The deployment plan determines how many infrastructures need to be deployed along roadsides and their optimal locations. The deployment problem is studied from two dimensions.

From the space dimension, the deployment in the X-Y plane is planned by big data analysis. First, using the map information and the transmission range of directional mmWave, the lowest number of infrastructures can be calculated to satisfy the full coverage of all roads. Second, limited by the size of an antenna array, one infrastructure can serve only a finite number of vehicles simultaneously. The redundant coefficient is derived according to historical road conditions; for example, high redundancy is set for roads with frequent congestion or accidents. Leveraging the above two steps, the total number of infrastructures and their rough distribution are obtained. However, it can be proved that it is NP-hard to find their optimal locations. We adopt the combinatorial optimization method to reach a sub-optimal result. In the Z-axis, the height of an infrastructure's antennas follows the rule that a height which is too low too

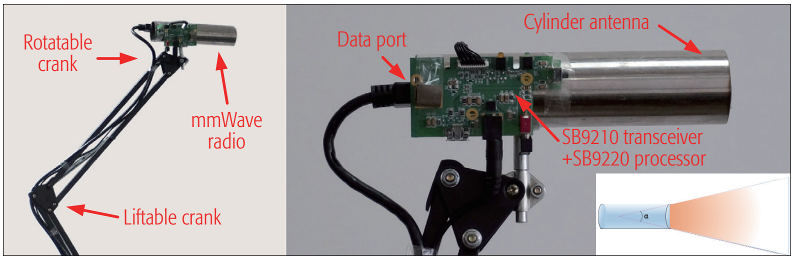

Figure 3. The prototype of a vehicular mmWave system, the crank arm, the cylinder antenna, and the beam model.

low will be blocked frequently, and a height that is too high will increase the path loss in long-distance transmission.

The view from the time dimension is also interesting and practical. We can imagine that the deployment of roadside infrastructures in an urban environment is a pretty long process. Similarly, the promotion of autonomous vehicles cannot be accomplished overnight. The report in *IEEE Spectrum* forecasted that the first vehicle with V2V and V2I communications would come into the market in 2018, and half of new cars will be autonomous by 2032. Hence, even if the optimal locations for deployment have been obtained, the deployment sequence should be further studied to keep pace with the market. We attempt to use economics theory to formulate the relationship between the numbers of infrastructures and vehicles with mmWave communications. Moreover, simulations based on the relationship are conducted to guide and amend the deployment plan.

Beam Control

Directional transmission is required in mmWave to overcome the path loss. To realize it, the directional antenna and beamforming are two candidate methods.

The major advantage of a *directional antenna* is its mature technology, as it is easy to implement at the current time using off-the-shelf devices. In [11, 13], a single horn antenna is adopted to concentrate the signal into a 7° beam, and a motor supports the rotation of this antenna. However, the drawbacks include the fact that one antenna provides only one wireless link, and the rotation motor introduces additional delay.

Beamforming can generate multiple links simultaneously by antenna array, and its direction change is fast enough to catch up with the vehicle's speed. Nevertheless, smart array devices are rare in the market. It is envisioned that beamforming will be a core technique in vehicular mmWave systems.

Using antenna array, the beam formation can be realized in the digital or analog domain. Digital beamforming is carried out by multiplying a particular coefficient to the modulated baseband signal. The strengths of digital beamforming include a higher degree of freedom and better transmission performance. Nevertheless, its drawback is the high complexity including the separate fast Fourier transform (FFT)/inverse FFT (IFFT) blocks, digital-to-analog converters (DACs), and analog-to-digital converters (ADCs) for every link. On the contrary, analog beamforming is a simple and effective method that generates high beamforming gains by controlling phase shifters and variable gain amplifiers. However, analog beamforming requires a large number of antennas, and it is less flexible than the digital method.

The trade-off between flexibility and simplicity motivates us to propose a hybrid structure. In this structure, simple analog beamforming is used to quickly track high-speed vehicles, while flexible digital beamforming provides multiple beams if one infrastructure needs to connect multiple vehicles simultaneously.

Handover Strategy

In conventional cellular networks, handover occurs when an established wireless link is redirected from the current cell to another. Compared to cellular networks, handover in vehicular mmWave communications is more complicated, which might be conducted as follows:

- When the vehicle is driving away from the coverage area of one mmWave radio and entering another radio's, the wireless link is transferred in order to avoid link termination. Even in this case, the handover operation is nontrivial because the vehicle has not only the V2I communication mode but also the V2V mode, which increases the destination diversity for handover.
- When one vehicle's wireless link is blocked by an object, such as a tree, a human, or other vehicles, this link has to be transferred to another mmWave radio quickly. Such a case never happens in cellular networks due to strong penetration capability. However, it is common in vehicular mmWave systems because of the directional transmission, poor penetration, and high speed.

Besides inheriting the state-of-the-art handover solution, we propose to add a prediction strategy to improve the handover performance. With the assistance of cloud computing, a vehicle can predict relatively precisely the movements of surrounding objects based on sensory data. Then, with the road map and the infrastructure locations, this vehicle schedules its handover beforehand with the objective of the optimal link selection constrained by bypassing the potential obstacles and minimizing the back-and-forth case.

Prototype and Evaluation

Prototype: To demonstrate the feasibility of a vehicular mmWave system, we build a prototype of 3D mmWave radio, shown in Fig. 3. This radio is supported by liftable and rotatable cranks, so its height and direction could be arbitrarily adjusted in 3D space, which can partially bypass the obstacle of line-of-sight communication. The radio frontend consists of a data port to exchange data with a computer, an SB9220 processor to operate the network control, an SB9210 transceiver to provide 4 Gb/s bit rate transmission in 60 GHz band, and a customized cylinder and metal waveguide as the antenna to form the signal into a beam. Then the beam can be considered as the cone model with the angle α. We conduct outdoor testing of a pair of such radios by HD video transmission. The angle α is nearly 9°, and the communication range is about 20 m without obvious lag.

Performance evaluation: Simulations are further conducted to evaluate the performance of vehicular mmWave systems. Our simulation is in a 100 m × 15 m (3 lanes each direction) road segment. Six infrastructures are deployed at locations {(0,0), (20,15), (40,0), (60,15), (80,0), (100,15)}. The number of autonomous vehicles varies from 20 to 100. All infrastructures and vehicles are equipped with mmWave systems. According to our prototype, the mmWave radio is liftable (height range 2–3 m) and rotatable, communication range is 20 m, and $\alpha = 9°$. The ratio of Priority I, II, III data is set 0.1:0–3:0.6. If two senders transmit data to one receiver, the sender with higher priority wins the link. We assume the antenna adjustment and the handover are quick enough without time delay.

Figure 4 illustrates the simulation result on the average number of effective wireless links, where one link is defined by two (end-to-end) or more (broadcast) connected radios. The comparison is between *mmWave* and *DSRC*; recall that DSRC is the 802.11p-based dedicated communication for vehicles. In Fig. 4, mmWave always performs better than DSRC, which demonstrates the efficient channel utilization by mmWave. If mmWave's multi-gigabit rate is further considered, its throughput in the whole network is much more than DSRC's, which has a maximal rate of 27 Mb/s. With the increase of density, the trends of two curves cannot maintain a linear increase because radios in each other's interference range cannot build new links. However, benefiting from the directional transmission, mmWave's trend slope is also better than DSRC's.

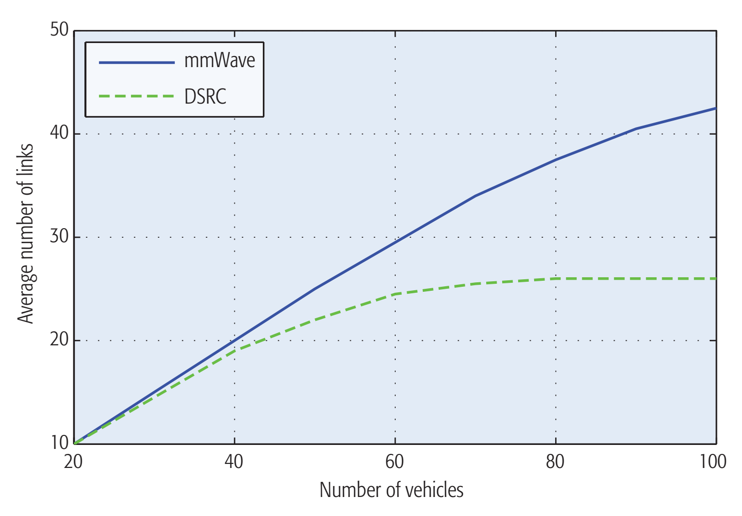

Figure 4. Average number of wireless links in simulation.

SUMMARY AND DISCUSSION

Both academia and industry have contributed considerable efforts on autonomous vehicles. Several projects, such as Google's driverless car, have been carried out to develop related standards, technologies, and applications. Millimeter-wave spectrum can potentially provide the ability of multi-gigabit transmission, which is the most effective and straightforward solution to support the communication for autonomous vehicles in the next few decades and beyond.

In this article, we design an IoT-cloud supported vehicular mmWave system to fully exploit the advantages of mmWave and vehicles. On one hand, this system enables sensory data sharing among vehicles to tackle the blind area and bad weather problems. On the other hand, toward the accurate recognition of human gestures and small objects, this system leverages cloud computing via V2I communication of HD video.

Using mmWave in autonomous vehicles is a new concept. Several open issues are worth being deeply studied in the future. First, it is very important to build a systematical theory for vehicular mmWave systems. The theoretical derivation of data redundancy, trajectory prediction, and throughput could guide the design, strategy determination, and parameter setting. Second, the security and privacy mechanism is also an open issue. Traffic data sharing may expose one's location and trajectory, resulting in privacy leakage. It is desired to design a privacy preservation component for mmWave communications. Third, the proposed system still lacks an incentive mechanism. Such a mechanism is helpful to encourage more users to participate in data sharing for more accurate self-driving optimization.

The framework of a vehicular mmWave system also produces several promising research directions. One valuable direction is to apply mmWave communications for other emerging applications, not only self-driving but also other mobile applications, such as entertainment and social networks, which demand big data transmission in high-speed environments. Moreover, a hybrid communication system is another practical direction. According to the above analysis, different wireless technologies possess different advantages. For example, Bluetooth is low-power and 4G covers a long transmission range. A communication system that consists of multiple wireless technologies can deal with complex requirements. Last but not least, since mmWave ensures adequate traffic data, a multi-modal data-based self-driving strategy can be studied to enhance the performance of self-driving.

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BIOGRAPHIES

LINGHE KONG (linghe.kong@cs.sjtu.edu.cn) is currently an associate professor with the Department of Computer Science and Engineering at Shanghai Jiao Tong University, P. R. China. Before that, he was a postdoctoral researcher at Columbia University, McGill University, and Singapore University of Technology and Design. He received his Ph.D. degree from Shanghai Jiao Tong University in 2012, his Master's degree from Telecom SudParis in 2007, and his B. E. degree from Xidian University in 2005. His research interests include wireless communication, sensor networks, mobile computing, Internet of things, and smart energy systems.

MUHAMMAD KHURRAM KHAN [SM] (mkhurram@ksu.edu.sa) is currently working as a full professor at the Center of Excellence in Information Assurance (CoEIA), King Saud University, Kingdom of Saudi Arabia. He is the Editor-in-Chief of the well reputed journal *Telecommunication Systems*. He is also on the Editorial Boards of several journals published by IEEE, Elsevier, Springer, Wiley, and others. He is an author of 275 research publications and an inventor of 10 U.S./PCT patents. His research areas of interest are cybersecurity, digital authentication, biometrics, multimedia security, and technological innovation management. He is a Fellow of the IET, BCS, and FTRA, a member of the IEEE Technical Committee on Security & Privacy, and a member of the IEEE Cybersecurity community.

FAN WU (fwu@cs.sjtu.edu.cn) is an associate professor in the Department of Computer Science and Engineering at Shanghai Jiao Tong University. He received his B.S. in computer science from Nanjing University in 2004, and his Ph.D. in computer science and engineering from the State University of New York at Buffalo in 2009. He visited the University of Illinois at Urbana-Champaign as a postdoctoral research associate. His research interests include wireless networking and mobile computing, algorithmic network economics, and privacy preservation.

GUIHAI CHEN (gchen@cs.sjtu.edu.cn) earned his B.S. degree from Nanjing University in 1984, his M.E. degree from Southeast University in 1987, and his Ph.D. degree from the University of Hong Kong in 1997. He is a Distinguished Professor of Shanghai Jiao Tong University. He had been invited as a visiting professor by many universities including the Kyushu Institute of Technology, Japan, in 1998, the University of Queensland, Australia, in 2000, and Wayne State University, Michigan, from September 2001 to August 2003. He has a wide range of research interests with focus on sensor networks, peer-to-peer computing, high-performance computer architecture, and combinatorics.

PENG ZENG (zp@sia.cn) received his B.S. degree in computer science from Shandong University in 1998 and his Ph.D. degree in mechatronic engineering from Shenyang Institute of Automation (SIA), Chinese Academy of Sciences (CAS), in 2005. Currently, he is a professor and Ph.D. supervisor at SIA, CAS. His research interests include industrial communication, smart grids,demand response, and wireless sensor networks. He is a member of IEC TC65 WG16 and a member of the SP100 Standard Committee, ISA.