Fifth-Generation Technologies for the Connected Car

Capable Systems for Vehicle-to-Anything Communications

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Two strong technology trends, one in the mobile communications industry and the other in the automotive industry, are becoming interwoven and will jointly provide new capabilities and functionality for upcoming intelligent transport systems (ITSs) and future driving. The automotive industry is on a path where vehicles are continuously becoming more aware of their environment due to the addition of various types of integrated sensors. At the same time, the amount of automation in vehicles increases, which, with some intermediate steps, will eventually culminate in fully automated driving without human intervention. Along this path, the amount of interactions rises, both in-between vehicles and between vehicles and other road users, and with an increasingly intelligent road infrastructure. As a consequence, the significance and reliance on capable communication systems for vehicle-to-anything (V2X) communication is becoming a key asset that will enhance the performance of automated driving and increase further road traffic safety with combination of sensor-based technologies [1].

On the other hand, the mobile communications industry has connected more than 5 billion people over the last 25 years, and mobile phones have become part of our daily living. The next step in wireless connectivity is to link all kinds of devices, with a total of 28 billion connected devices predicted by 2021.

The Fifth-Generation (5G) Communication Automotive Research and innovation (5GCAR) project [2] is a 5G public-private partnership phase-two project, which brings together a consortium from the automotive industry, the mobile communications industry, and academia. The goal of the project is to develop technologies at the intersection of automotive and mobile communication sectors to support a fast and successful path toward safer, more efficient future driving. The key objectives of 5GCAR are to reduce end-to-end latency, improve reliability, ensure high availability, guarantee interoperability of heterogeneous radio technologies, increase scalability (i.e., massive access), and secure vehicular communications. Figure 1 illustrates the 5GCAR concept and its key technical components, such as 5G radio resource management, 5G radio-assisted positioning, multilink and multi-Radio Access Technology (multi-RAT) connectivity, nonassisted/assisted sidelink, diversity techniques, 5G mobility management, software-defined networking 5G V2X slice, security, and privacy.

V2X Channel Measurements and Modeling

The propagation channel is one of the key performance factors that impacts any communication system. High speed of the vehicles, dynamic surroundings often cluttered with static and mobile scatterers, and low antenna

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heights create challenges for V2X communications that are unique compared to other communication systems. Furthermore, the variety of applications envisioned that the 5G V2X system aims to support, ranging from basic safety applications [3] to high-precision radio positioning and advanced cooperative automated driving applications (e.g., platooning, cooperative intersection control, and so on), results in considerably different requirements in terms of channel modeling.

Several V2X-specific channel models have been developed covering dozens of scenarios and environments based on analytical as well as empirical data analysis. Two recent surveys of these models are available in [4] and [5]. Given the number of scenarios, environments, and classification of models with regard to modeling approaches (Figure 2), there can be hundreds of combinations, which makes it difficult to do a right selection of model parameters. The channel models in context of wireless system design are often used to perform the sensitivity or benchmarking of the chipsets, to gather performance statistics and test protocol applications while simulating end-to-end system performance. A detailed recipe, which could guide the system designers to be able to choose the appropriate V2X channel model is not explicitly available in the literature. Toward providing such a recipe, this section summarizes the key ingredients for selecting appropriate channel models, which are a starting point for a more detailed classification, gap analysis, and further measurements and modeling that will be performed within the 5GCAR project.

THE GOAL OF THE PROJECT IS TO DEVELOP TECHNOLOGIES AT THE INTERSECTION OF AUTOMOTIVE AND MOBILE COMMUNICATION SECTORS TO SUPPORT A FAST AND SUCCESSFUL PATH TOWARD SAFER, MORE EFFICIENT FUTURE DRIVING.

The key components required for correct parametrization of V2X channels are summarized in Figure 2. V2X communication is diverse in terms of both environments where it occurs as well as the type of actors involved in the communication (top half of Figure 2). Therefore, the measurements and model parameterization need to take into account the proper environment (e.g., highway, rural, or urban), as well as the link type [e.g., vehicle to vehicle (V2V), vehicle to infrastructure, vehicle to pedestrian]. Next, the dimensions of vehicles and the location of antennas on them have a profound effect on the resulting channel: a channel between roof-mounted antennas on two suburban utility vehicles will be considerably different than a channel between two bumper-level antennas on two personal cars.

Once the link type and antenna locations have been selected and, depending on the target application and

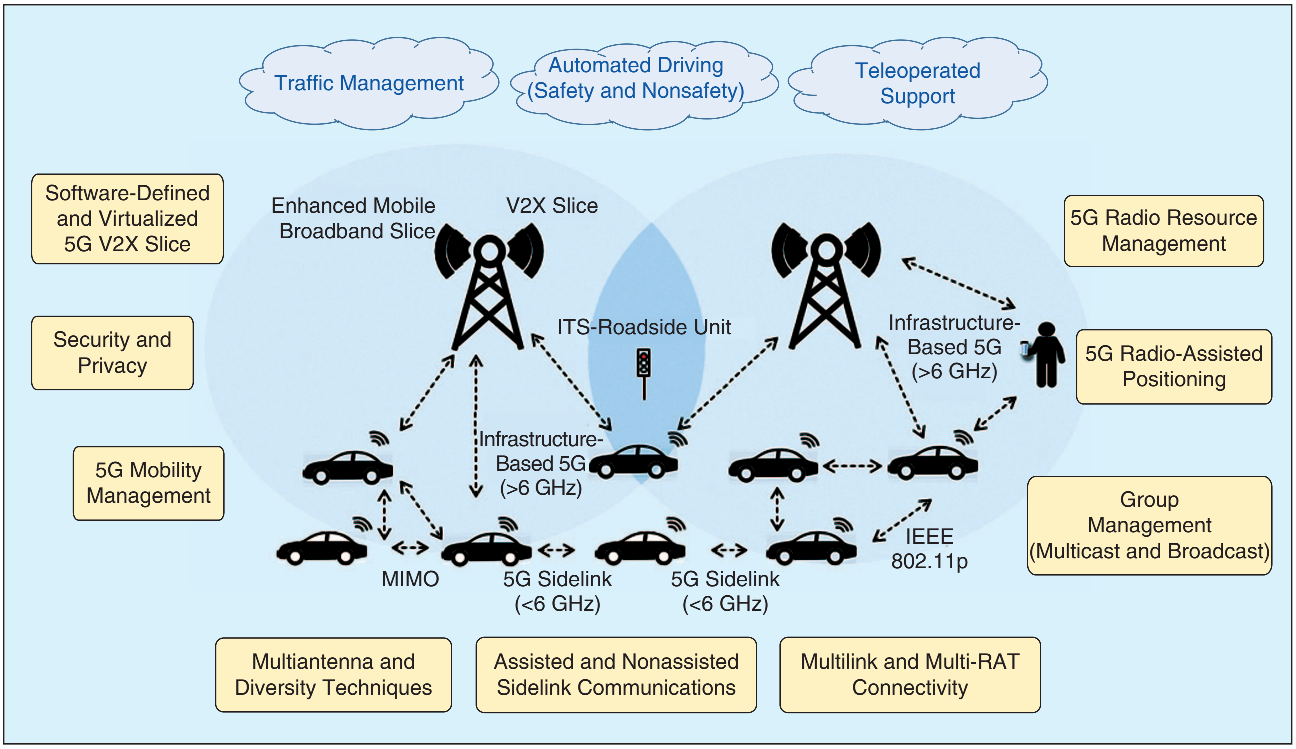


FIGURE 1 The 5GCAR concept and its key technical components. MIMO: multiple input, multiple output.

Environment

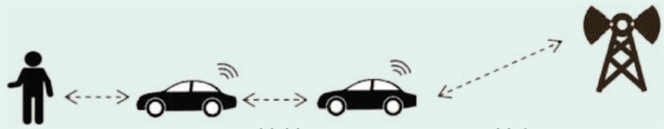
Rural

Highway

Urban

Special Scenarios
- Tunnel
- Bridge
- Covered Parking
- Multilevel Roads

Link Type



V2P V2V V2I

Vehicle Type and Antenna Location
- Motorcycle
- Cars (Sedan, SUV, Hatchback)
- Bus
- Truck

Shadowing and Propagation Conditions
- LOS: Line-of-Sight
- Non-LOSv: LOS Blocked by Larger Objects on Road (Other Vehicles)
- Non-LOSb: LOS Blocked by Nearby Buildings

V2X Channel Model Components and Their Availability in State of the Art		Model Exists/Effect Accounted for in the State of the Art: <6 GHz	Model Exists/Effect Accounted for in the State of the Art: >6 GHz
Propagation Mechanism	• LOS Blockage	+V2X	+V2X
	• Path Loss	+V2X	+V2I; –V2V/P
	• Shadow Fading	+V2X	+V2I; –V2V/P
	• Small-Scale Fading	+V2X	+V2I; –V2V/P
	• Corrected Fading Effects for Single and Multilinks	+V2I/V; N/A V2P	+V2I; –V2V/P
Modeling Approach	• Nongeometry-Based (e.g., Tapped Delay Line)	+V2I/V; –V2P	+V2I/V; –V2P
	• Geometry-Based Deterministic	+V2X	+V2I; –V2V/P
	• Geometry-Based Stochastic	+V2I/V; –V2P	V2I; –V2V/P

Model Properties	Must Have	Good to Have
	• Spatial-Temporal Dependencies (esp_for V2V)	• Extensibility
	• Nonstationarity (esp_for V2V)	• Double Directional, Antenna Configuration Dependency
	• Applicability	• Scalability and Complexity

FIGURE 2 V2X-specific considerations for channel modeling. For each link type [i.e., V2V, vehicle to pedestrian (V2P), and vehicle to infrastructure (V2I)], we indicate whether an appropriate model exists ("+") or not ("–") in the literature. For further details, see [4]–[6]. SUV: sport utility vehicle.

the target performance metric, channel models can be classified as follows:

1) Nongeometry-based stochastic (NGS) models are based on statistics extracted from a set of representative measurements for a given environment. They are simple to use and computationally inexpensive. NGS models will typically apply for a specific propagation condition [e.g., line of sight (LOS)] and will either not incorporate or provide abstracted versions of more detailed mechanisms, such as correlated fading, spatiotemporal dependencies, LOS blockage, and so on. Tap-delay line models [6], a subgroup of NGS models, are useful when performing sensitivity testing or benchmarking of the wireless chipsets. They can be easily implemented in channel emulators.
2) Geometry-based deterministic (GBD) and GBD stochastic models can be used to evaluate the performance of link level protocols for analyzing network topology statistics, performance of protocols, or end-to-end application testing. Depending on the simulation scale and propagation mechanisms implemented, they are typically classified as link-level or system-level models [6]. Link-level models are mostly concerned with small-scale fading required to evaluate link-level performance, whereas they abstract away the large-scale fading effects. On the other hand, system-level models focus on large-scale evaluation and often abstract the small-scale aspects through link-to-system mapping.

Most prominent examples of GBD models are based on ray tracing/ray launching, whereas the model adopted by the 3rd Generation Partnership Project (3GPP) [6], based on the evolution of the Wireless World Initiative New Radio framework, is the most-often-used GBD model. However, up until now, 3GPP models in [6] do not implement some key V2X features, such as the impact of dual mobility on fast-fading parameters, which are necessary for V2V; they do not consider V2X-specific scenarios [e.g., highway, street-level urban, roadside unit (RSU)-to-vehicle, or V2V]; and have not considered V2X-specific antennas.

Cellular-Based V2X and Synchronization

Cellular-based V2X is considered the main radio interface to support 5G vehicular communication through three distinct modes: cellular V2X, cellular-assisted V2V, and cellular-unassisted V2V. Cellular V2X refers to classic uplink/downlink communication, where a vehicle communicates with a base station or RSU. RSUs will be deployed to improve coverage and throughput, as well as to reduce latency through fast radio access, handover, and coordinated resource allocation. Cellular-assisted V2V is a scheme where the base station coordinates communication between vehicles by providing control information and instructions to vehicles [3]. This mode is well-suited for extremely low latency and high-reliability V2V communication, as the network infrastructure ensures resource availability when requested and time-consuming data transmission over the cellular network is avoided. For some use cases (e.g., platooning and see-through), cellular V2V will provide traffic offloading, as data exchange between users in a certain geographical region can be realized by V2V. Finally, cellular-unassisted V2V is a mode where vehicles communicate without direct assistance from the base station. However, resources are still considered under the control of the cellular network. Out-of-coverage users further remain synchronized to the cellular network and follow a common time reference. In this sense, even out-of-coverage users can be considered as part of the cellular network and their transition to one of the other modes can be very fast. In all three modes, the cellular network controls, to different levels, the data transmission between vehicles and ensures that their needs in terms of data rate, reliability, and latency are satisfied.

V2X COMMUNICATION IS DIVERSE IN TERMS OF BOTH ENVIRONMENTS WHERE IT OCCURS AS WELL AS THE TYPE OF ACTORS INVOLVED IN THE COMMUNICATION.

One of the most challenging requirements of cellular-based V2X is time and frequency synchronization. Unlike IEEE 802.11p, long-term evolution (LTE)-based and 5G V2X will require users to be synchronized among each other to avoid intersymbol and intercarrier interference, which are caused by the misalignment of multicarrier signals transmitted over the air.

The coexistence of V2V and cellular V2X in one frequency band further needs the synchronization of base stations and RSUs, which is in contradiction with the typical scenario of nonsynchronized base stations of the same or different network operators. Distribution of a common time reference and agreement among all involved network entities must be achieved before any data communication can be established.

Figure 3 shows a vehicular network with partial cellular coverage. As a design guideline, it is recommended that users presynchronize within a larger area than the one for data exchange. In-coverage users follow the time reference provided by their serving base station, whereas out-of-coverage users will have to hierarchically select from available sources, such as global navigation satellite system (GNSS) or users transmitting synchronization signals in the sidelink. As proposed in [7], source selection and distributed algorithms need to be combined to achieve mutual synchronization. There, it was shown that in a network with 30 users (out of which ten are in coverage provided by the same base station, ten with GNSS,

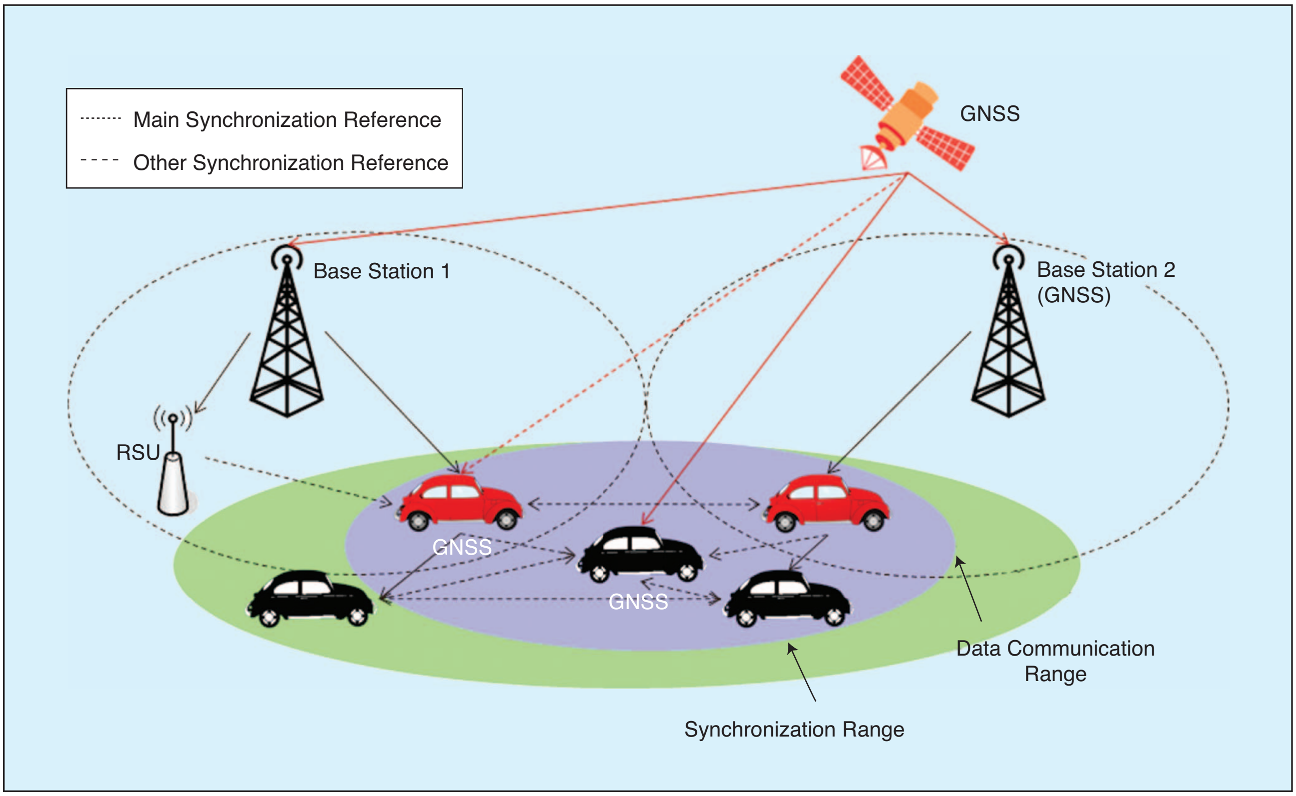


FIGURE 3 A scenario with in- and out-of-coverage vehicular users. GNSS may be available to some base stations, RSUs, and users. Synchronization source selection and distributed synchronization are used to achieve global synchronization.

and ten obtaining time reference through the sidelink), the proposed mutual synchronization method can reduce the residual timing offset to below 0.5 μs, which is smaller than the typical guard interval used for multicarrier waveforms. The cases of nonsynchronized base stations and synchronization between different operators' users need further study, while the design of the sidelink control channel and synchronization sequences will also require careful design for 5G V2X.

V2X Radio Access Architecture

Flexible network architecture is envisioned as one of the properties of 5G V2X networks to enable integrated seamless connectivity for multi-RAT, multilink operation, where ultralow latency and ultrahigh reliability should be supported for critical automotive communications. Such flexibilities can be foreseen in the software-based network control [8], placement of network functionalities [9], and design of the radio access network [10], which then can be realized through network slicing [11]. In this section, we focus on the flexibility in radio access network (RAN) design in terms of how the RAN functionalities can be placed in the fog (details in the "Fog Computing and the Connected Car" section), i.e., splitting the radio and baseband functionalities between central cloud and distributed entities.

Through 3GPP, eight options for splitting the functionalities in RAN have been introduced [12]. Among these options, we examine latency and jitter in the three options of the split between packet data convergence protocol and radio link control (PDCP-RLC), between medium access control and physical layer (MAC-PHY), and within physical layer (intra-PHY) within an experimental platform, using open-air interface, which is further explained in detail in [10] and [13]. The study is performed with traffic models of three classes of service in 5G, each representing a different application in connected cars. The ultrareliable low latency communication, representing safety messages and cooperative driving, massive machine-type communication, representing vehicles' sensors messages, and enhanced mobile broadband (eMBB) traffic, representing infotainment traffic in the vehicle [14]. The ultimate aim of this study is to show which split performs best for which of the application classes in V2X, assuming such a split can be achieved in a more dynamic way through software-defined networking (SDN) and fog computing.

Figure 4 shows latency and jitter introduced by each split (i.e., the time interval from when a packet transmission is triggered by the upper layer of the split to when the packet is successfully received by the lower layer of the split). We can note that the PDCP-RLC and MAC-PHY

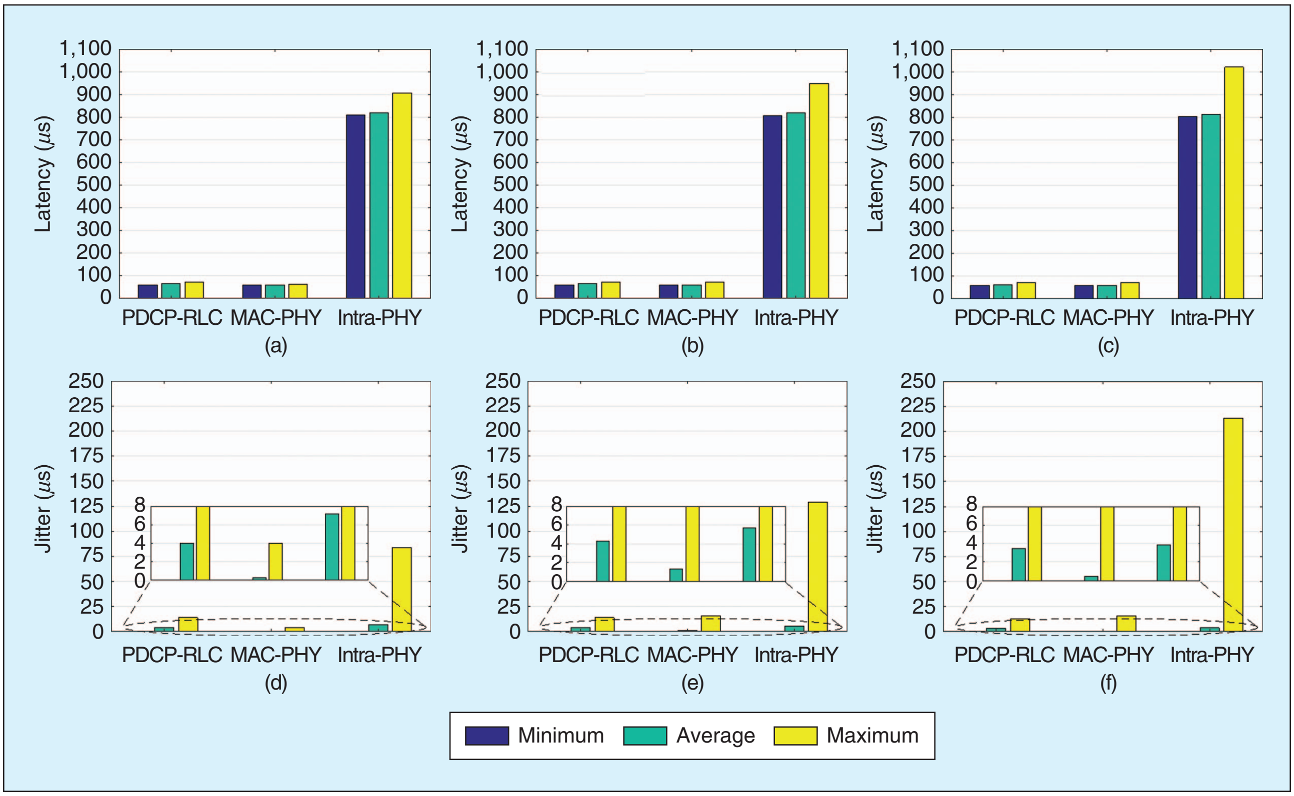


Figure 4 The latency and jitter for different splits for 5G services. The minimum jitter is equal to zero. The (a) latency eMBB, (b) latency massive machine-type communication (mMTC), (c) latency ultrareliable low-latency communication (URLLC), (d) jitter-eMBB, (e) jitter-mMTC, and (f) jitter-URLLC [10].

splits work in a more stable way compared to intra-PHY in terms of added latency. In detail, the average latency is almost constant for all of the splits and equal to ~65 μs for PDCP-RLC and ~60 μs for MAC-PHY. Observing from the jitter plots [Figure 4(d)–(f)], the lowest jitter is guaranteed by the MAC-PHY split, as the MAC and PHY layers work in a synchronous way, thus reducing the delay variation. Higher jitter is obtained for the PDCP-RLC split, as in this case, the PDCP sends a packet to RLC whenever it receives a packet from upper layers with higher latency variation. Finally, the highest jitter is obtained with the intra-PHY split due to the high number of packets (i.e., 14) transmitted every ms. The results presented in Figure 4 provides recommendation for when to move baseband functionalities of RAN to the cloud while serving different applications in connected cars.

Integrated Moving Networks

With 5G and its evolution, users will expect the connected society to be available with no limitations, and users will make use of bandwidth-demanding services like augmented reality and virtual office applications, also when on the move. In this context, future vehicles and transportation systems may play an important role in wireless networks by providing additional communication capabilities and becoming an integral part of the communication infrastructure to improve capacity and coverage of operator-driven mobile networks. That is, to serve vehicular users effectively, one promising solution is to deploy moving base stations on the vehicles to form moving networks (Figure 5) [15].

One of the purposes of the moving base stations is to effectively serve in-vehicle users, which is becoming more demanding for high data rate and low latency services with modern, well-insulated vehicles that have a very high penetration loss (≥25 dB) in combination with high carrier frequencies ranging up to millimeter-waves (≤100 GHz). Yet another important opportunity is to enable moving base stations to act also as cooperative ad-hoc small-cell base stations in the heterogeneous mobile networks to serve out-of-vehicle users [16].

Thus, there is a large unexplored potential to integrate moving base stations as ad hoc network elements into the heterogeneous mobile networks with mobile-operator-controlled network nodes to form integrated moving networks. However, there are also several key open research topics, including: 1) tracking a large set 2
of mobile channels at a high speed to enable advanced spectrally efficient and robust closed loop (i.e., massive) MIMO schemes in the moving backhaul links [17]; 2) designing closed-loop and cooperative interference

There is a vast unexplored potential to take advantage of various kinds of side information, like road infrastructure information, driving route information, positioning, and social networks.

coordination techniques in ultradense heterogeneous networks; 3) resource allocation and resource slicing for versatile quality of service services to meet key performance targets on outage, throughput, latency, and energy efficiency; and 4) enabling efficient mobility protocols in such integrated moving networks.

Designing such closed-loop cooperative transmission and resource allocation schemes efficiently in hybrid heterogeneous networks consisting of fixed and moving base stations is a challenge. However, there is a vast unexplored potential to take advantage of various kinds of side information, like road infrastructure information, driving route information, positioning, and social networks. By looking into such sources of information, there is also the potential along the way that a lot of new services with associated business models could emerge (more details in the "A Business Perspective for the Connected Car" section). Key challenges include handling privacy, security, and implementing authentication and owner protection of these information sources.

Integrated moving networks can also enable ultrareliable communication links to transport ITS messages between vehicles and mobile devices of so-called vulnerable road users, such as pedestrians, cyclists, playing children on the streets, pets, and so on, that are not equipped with dedicated communications transceivers for ITSs.

Modern vehicles are moving multisensor systems that are constantly collecting information. As such, they could be used to support development of smart city applications, such as air quality sensors, road maintenance support, noise level monitors, weather forecasts, traffic congestion levels for route optimization of critical transports, and so on. One opportunity that remains to be explored is how municipalities could use this information to optimize the resource efficiency and improve the quality of life in crowded cities.

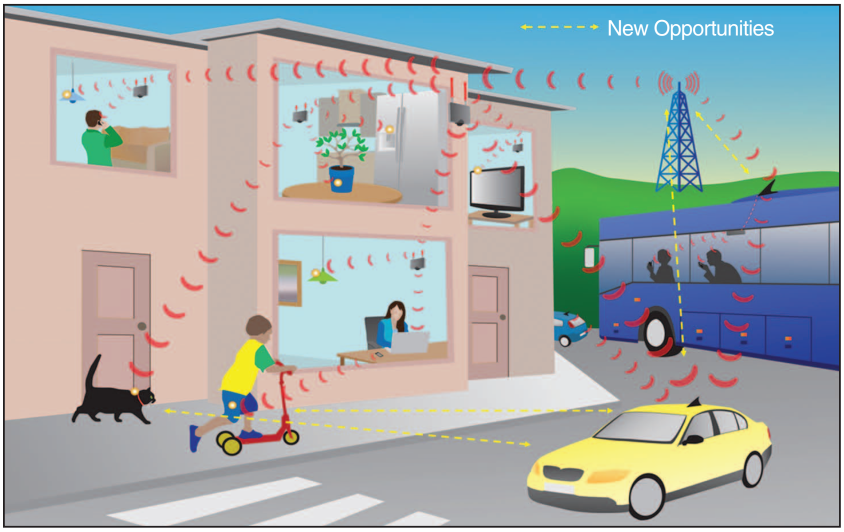


Figure 5 An illustration of integrated moving networks.

Fog Computing and the Connected Car

Understanding the connected car as a complex cyberphysical system, many of the communication techniques designed for the Internet of Things (IoT) and fog computing can be applied and adapted to networks supporting connected vehicles. This includes optimized wireless communication protocols, data formatting protocols, cloud and fog computing, SDN, and network function virtualization (NFV), among others.

Fog computing is a system-level architecture to extend compute, network, and storage capabilities of the cloud to the edge of the network. In the context of fog computing, the SDN paradigm enables a global orchestration of all network resources including the management of distributed fog and cloud domains and the coexistence of heterogeneous networks combining different types of communication technologies. NFV has introduced a novel paradigm where services can be deployed on demand to fulfill the end-user's needs. These three techniques (i.e., fog computing, SDN, and NFV) are intertwined; in future communication networks, services will be deployed over a cloud computing infrastructure, where the necessary connectivity is provided by an SDN controller.

Using a service orchestrator for IoT applications was previously proposed in [18]. Under this context, the SDN orchestrator must carry out the following three key functions: 1) facilitate the transport of the huge amount of data generated at the terminals, sensors, machines, nodes, and more to any distributed computing node, edge, or core data center; 2) allocate computing and storage resources in distributed fog nodes and data centers; and 3) process the collected data to make proper decisions, leading to the concept of cognition.

Figure 6 shows the proposed location for fog computing in a connected car environment:

- A fog node could be inserted inside the car to offer the various third-party original equipment manufacturer services and applications on top of the same infrastructure (e.g., lane merge, see through, file-transfer-protocol client, or video client). This approach would simplify the vehicle control architecture and reduce the control system weight and cost of software development.

- Following multiaccess edge computing architecture, a fog node could be located on the base transceiver station, where RAN information can be accessed in real time. Moreover, this location could allow the allocation of ITS services and applications near the edge of the network to provide low latency.

Beyond connectivity, the ultimate key element here is the data, from which real value can be obtained. In the end, connectivity is just the means to gather and obtain the data. When it comes to processing the data, formatting it becomes a key design decision. The adoption of a common, flexible, and powerful data and information modeling language to define all sensors, actuators, gateway facilities, and services is a first important step toward the standardization of IoT frameworks across multiple vendors beyond the existing ones, and the automotive sector is not an exception.

Network Configuration Protocol (NETCONF) and Yet Another Next Generation (YANG) [19] provide the tools that network administrators need to automate configuration tasks across heterogeneous devices in an SDN. For such purpose, YANG data models need to be complemented with NETCONF/RESTCONF protocols [20]. These protocols enable the control and management of YANG data models. Among other options, over the last years, YANG [21] data modeling language has been steadily growing in the information technology and networking communities as a data modeling language suitable for the IoT.

MODERN VEHICLES ARE MOVING MULTISENSOR SYSTEMS THAT ARE CONSTANTLY COLLECTING INFORMATION.

A Business Perspective for the Connected Car

A major change for business models will be 5G, enabling new services and improving the existing ones. More specifically, 5G brings technology enablers in the areas of radio access technology for V2X communications and virtualization of the communications network, from the radio to the core.

These enablers will bring components such as network slicing, mobile edge computing, cellular radio-based positioning and tracking, and sidelink. However, these components by themselves cannot guarantee the creation of new business opportunities, but how they affect business relationships is important. With the example of network slicing, each slice could work in isolation for different types of service; this enables separate accounting and billing depending on the properties and reflecting the throughput, latency, and data consumption of the V2X services.

More important, the automotive sector has typically been an example of a well-defined and specialized value

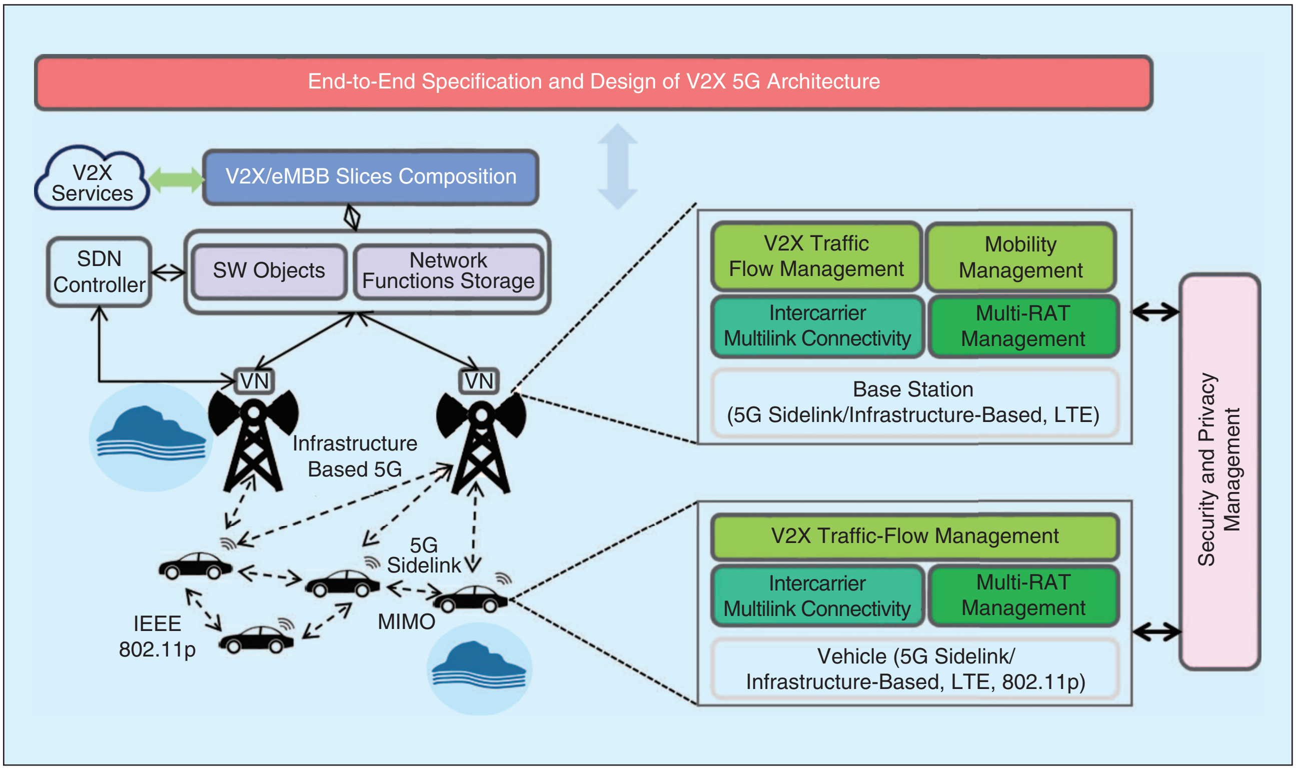


FIGURE 6 Fog computing architecture. SW: software; VN: virtual network.

A MAJOR CHANGE FOR BUSINESS MODELS WILL BE 5G, ENABLING NEW SERVICES AND IMPROVING THE EXISTING ONES.

chain. The automotive industry had a linear development going from suppliers of raw materials and basic components to more complex components, vehicle manufacturers, dealers, and, finally, the aftermarket sector. However, due to connectivity and driven by new 5G technologies, the value chain is transforming into a value network. This term refers to having aligned business models instead of a chain with each actor giving value from left to right until the end product. Value networks are examples of economic ecosystems, where every node in the network relies on others to create a common value proposition [22]. The existing value chain and how services and features are enabled will be impacted by 5G. These technologies have the capacity to disrupt current business relationships and create more collaborative business environments, since it is rare for a single company to have every competence required to create a vertical solution with the increasing demands of new technologies and cross-industrial ecosystems. Therefore, cooperation both within and between different sectors is needed.

There are two main drivers for new services. The first comes from clear business cases that are pushed directly in the private sector (infotainment, over-the-air software updates, or high-definition maps). The second is from regulatory mandates, such as the case for e-call services in Europe. The latter is the focus where value proposition revolves around societal benefits, which is the case for road safety issues, including the implications on regulation.

One straightforward view is to leverage the adoption of infotainment services to amortize the investment cost on safety features, but other alternatives are needed when infotainment services cannot drive deployment costs. For instance, providing incentives for mobile network operators to expand coverage in currently underserved areas with low mobile broadband traffic demand; such incentives could come in the form of extending spectrum licenses with the compromise of requesting coverage expansion. Another option is to foster infrastructure sharing along roads, which could be provided by road operators or tower companies.

Conclusions

We have presented a selected set of topics that are necessary for achieving the 5G connected car. A significant topic is the characteristics of the underlying V2X channels. We have also introduced the main building blocks of a cellular V2X solution. A flexible network architecture has been presented to support advanced V2X services. We have also explored the potential of using vehicles in the form of mobile base stations as part of that flexible architecture. Fog computing has been presented in the context of the connected car, and finally a business ecosystem surrounding connected cars has been explored.

Further work on these current research topics will allow the fast introduction of the 5G connected car.

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References

[1] K. David and A. Flach, "Car-2-x and pedestrian safety," *IEEE Veh. Technol. Mag.*, vol. 5, no. 1, pp. 70–76, 2010.

[2] The 5G Infrastructure Public-Private Partnership. (2017). 5GCAR. [Online]. Available: https://5gcar.eu/

[3] 3G Partnership Project. (2015, Sept.). 3GPP TR 22.885 V1.0.0: Study on LTE support for V2X services (Release 14). [Online]. Available: https://www.slideshare.net/yihsuehtsai/3gpp-tr-22885-study-on-lte-support-for-v2x-services

[4] D. W. Matolak, *V2V Communication Channels: State of Knowledge, New Results, and What's Next*. Berlin, Germany: Springer Berlin Heidelberg, 2013, pp. 1–21.

[5] W. Viriyasitavat, M. Boban, H. M. Tsai, and A. Vasilakos, "Vehicular communications: Survey and challenges of channel and propagation models," *IEEE Veh. Technol. Mag.*, vol. 10, no. 2, pp. 55–66, June 2015.

[6] European Telecommunications Standards Institute. (2017, Sept.). 3GPP TR 38.901 V14.2.0: Study on channel model for frequencies from 0.5 to 100 GHz. [Online]. Available: http://www.etsi.org/deliver/etsi_tr/138900_138999/138901/14.00.00_60/tr_138901v140000p.pdf

[7] K. Manolakis and W. Xu, "Time synchronization for multi-link D2D/V2X communication," in *Proc. IEEE 84th Vehicular Technology Conf. (VTC)*, 2016, pp. 1–6.

[8] T. Mahmoodi and S. Seetharaman, "Traffic jam: Handling the increasing volume of mobile data traffic," *IEEE Veh. Technol. Mag.*, vol. 9, no. 3, pp. 56–62, Sept. 2014.

[9] P. Vizzareta, M. Condoluci, C. M. Machuca, T. Mahmoodi, and W. Kellerer, "QoS-driven function placement reducing expenditures in NFV deployments," in *Proc. IEEE Int. Con. Communications*, May 2017, pp. 1–7.

[10] G. Mountaser, M. Condoluci, T. Mahmoodi, M. Dohler, and I. Mings, "Cloud-RAN in support of URLLC," *IEEE GLOBECOM Workshops*, Dec. 2017, pp. 1–6.

[11] M. Jiang, M. Condoluci, and T. Mahmoodi, "Network slicing in 5G: An auction-based model," in *Proc. IEEE Int. Con. Communications*, May 2017, pp. 1–6.

[12] J. M. Meredith, "Study on new radio access technology: Radio access architecture and interfaces," Nippon Telegraph and Telephone DOCOMO, INC., Tokyo, Japan, Tech. Rep. R3-161687, Draft TR 38.801, Aug. 2016.

[13] G. Mountaser, M. L. Rosas, T. Mahmoodi, and M. Dohler, "On the feasibility of MAC and PHY split in cloud RAN," in *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Mar. 2017, pp. 1–6.

[14] The 5G Infrastructure Public-Private Partnership. (2016, Apr.). 5G PPP use cases and performance evaluation models. [Online]. Available: https://5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-use-cases-and-performance-evaluation-modeling_v1.0.pdf

[15] Y. Sui, A. Papadogiannis, J. Vihril, M. Sternad, W. Yang, and T. Svensson, "Moving cells: A promising solution to boost performance for vehicular users," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 62–68, June 2013.

[16] X. Tang, X. Xu, T. Svensson, and X. Tao. (2017). Coverage performance of joint transmission for moving relay enabled cellular networks in dense urban scenarios. *IEEE Access*. [Online]. *5*, pp. 13,001–13,009. Available: https://research.chalmers.se/publication/ 251714

[17] D. T. Phan-Huy, M. Sternad, and T. Svensson, "Making 5G adaptive antennas work for very fast moving vehicles," *IEEE Intell. Transp. Syst. Mag.*, vol. 7, no. 2, pp. 71–84, 2015.

[18] R. Vilalta, I. Popescu, A. Mayoral, X. Cao, R. Casellas, N. Yoshikane, R. Martínez, T. Tsuritani, I. Morita, and R. Muñoz, "End-to-end sdn/nfv orchestration of video analytics using edge and cloud computing over programmable optical networks," in *Proc. IEEE Optical Fiber Communications Conf. and Exhibition (OFC)*, 2017, pp. 1–3.

[19] M. Bjorklund. (2010). Yang—A data modeling language for netconf. *Internet Eng. Task Force*. [Online]. pp. 1–172. Available: https://tools.ietf.org/html/rfc6020

[20] A. Bierman, M. Bjorklund, and K. Watsen. (2017). Restconf protocol. *Internet Eng. Task Force*. [Online]. pp. 1–96. Available: https://tools.ietf.org/html/rfc8040

[21] M. Yannuzzi, F. van Lingen, A. Jain, O. L. Parellada, M. M. Flores, D. Carrera, J. L. Pérez, D. Montero, P. Chacin, and A. Corsaro, "A new era for cities with fog computing," *IEEE Internet Comput.*, vol. 21, no. 2, pp. 54–67, 2017.

[22] R. Adner, "Ecosystem as structure," *J. Manage.*, vol. 43, no. 1, pp. 39–58, 2017.

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