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5G mm-Wave Positioning for Vehicular Networks

Henk Wymeersch, Gonzalo Seco-Granados, Giuseppe Destino, Davide Dardari, and Fredrik Tufvesson

Abstract

5G technologies present a new paradigm to provide connectivity to vehicles, in support of high data-rate services, complementing existing inter-vehicle communication standards based on IEEE 802.11p. As we will argue, the specific signal characteristics of 5G communication turn out to be highly conducive for vehicle positioning. Hence, 5G can work in synergy with existing on-vehicle positioning and mapping systems to provide redundancy for certain applications, in particular automated driving. This article provides an overview of the evolution of cellular positioning and discusses the key properties of 5G as they relate to vehicular positioning. Open research challenges will be presented.

I. Requirements for Vehicular Positioning

With the increase of automated driving in various forms (highway assistance driving, automatic cruise control, self-parking, up to fully autonomous driving), comes a need for precise positioning information. Positioning of vehicles is achieved through a variety of technologies, as illustrated in Fig. 2, including global navigation satellite-based systems (GNSS), radar, mono and stereo cameras, and laser scanners (lidar), which are fused to give the vehicle an understanding of the environment and its location within

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this environment. The environment is encoded through a map, which is either stored offline or computed online. The process of learning the environment and building detailed maps is known as mapping. Different positioning applications have different requirements, which are expressed in terms of *accuracy*, *latency*, *reliability*, and *cost*. On the one hand, standard vehicular navigation applications require only a few meters of absolute positioning accuracy, second-level latency, low reliability (frequent outages are tolerable), but must rely on low-cost sensors. On the other hand, the safety-critical application of autonomous driving will require centimeter-level absolute and relative positioning accuracy, latencies on the order of tens of milliseconds, and high reliability, but can rely on a more expensive suite of sensors. An overview of the accuracy requirements for several key applications is shown in Fig. 1.

GNSS, which has been the workhorse for vehicular absolute positioning in military, professional, and personal navigation, leads to uncertainties on the order of a few meters. Complemented with dedicated base stations, real-time kinematic GNSS further improves the accuracy down to the centimeter level. However, GNSS fails to work in certain common conditions, such as under tree canopies, in the presence of GNSS jammers, and in dense urban environments, due to blocking of GNSS signals by buildings. Moreover, GNSS is limited by significant latency and low refresh rate, which are key requirements for guaranteeing safety.

For relative positioning, on-board sensors such as camera, radar and lidar can generally operate well under these GNSS-challenged conditions, and provide very precise information. However, these sensors are costly in terms of computational effort, due to the large amounts of data that need to be processed and the need to recognize and classify objects in the environment. Moreover, adverse weather conditions, such as fog, snow, and rain, might compromise camera- and lidar-based measurements and increase false object recognition and tracking. For absolute positioning, these sensors must combine measurements with a high-definition map. In particular, measured features (e.g., lamp posts, lane markings) are compared with information in the map in order to provide accurate absolute positioning. The mapping process, i.e., the establishment and maintenance of such maps is costly and time-consuming, and cannot capture effects such as road works or temporary road closures, making them unsuitable as sole positioning technique for critical applications. Moreover, high-quality on-board sensors are still costly, which renders them inappropriate for large-scale commercial applications.

We observe that vehicle positioning relies on a large combination of different sensors, suitable for different ranges, different weather conditions, and with different trade-offs. A positioning technology that has so-far not been considered in a vehicular context is the cellular radio infrastructure. Cellular signals are ubiquitous, inexpensive to obtain and process, and require no additional hardware. The reason cellular positioning has never been considered lies in its poor accuracy. It is our hypothesis that this limitation will be finally overcome with the introduction of 5G wireless communication systems.

II. 5G for Accurate Positioning

While there is not yet a fully defined 5G standard, 5G systems will exhibit a number of properties that are useful for providing accurate position information: high carrier frequencies (far above 3 GHz), large bandwidths (possibly hundreds of MHz), large antenna arrays (enabled by very short wavelengths), direct device-to-device (D2D) communication, and network densification. Before we explore these properties, we give a brief overview of the history of cellular positioning.

A. Cellular Positioning

For applications where accuracy is less important, cellular technologies have been utilized for positioning for decades (see Fig. 3). Such positioning does not imply significant dedicated deployments and maintenance cost, since it relies on existing communication infrastructure. For instance, 2G communication provided cell-ID based positioning, with accuracies on the order of a few hundred meters. Using time-difference of arrival (TDOA) measurements, the accuracy could be improved to tens of meters in 3G and, more plausibly so in LTE with dedicated pilot patterns. However, none of these cellular generations can currently meet the positioning requirements of future vehicular networks, shown in Fig. 1. In contrast, 5G systems will have several unique features that make them conducive for vehicular positioning. This means that 5G has the potential to provide positioning services with accuracies beyond GNSS with limited additional cost, using existing infrastructure, and with negligible overhead to the communication, in terms of time-frequency resources. In turn, 5G positioning will benefit from dedicated reference signals, as well as dedicated protocols, software, and servers.

B. The 5 Selling Points of 5G Positioning

1) High carrier frequencies: At higher carrier frequencies (around 30 GHz and above), in the mm-wave band, path loss becomes a more important impairment than in lower bands, requiring dedicated compensation techniques at both the transmitter and receiver. These techniques can include highly directional antennas and beamforming. At mm-wave, the small signal wavelength (10 mm at 30 GHz) allows packing hundreds of antenna elements in a small area, giving the possibility to realize highly directional beamforming capabilities. Severe penetration loss and high diffraction loss lead to propagation dominated by the line-of-sight (LOS) component and very few reflected paths. Consequently, the channel becomes (i) sparse in the sense of few dominant multipath components; and (ii) highly dependent on the positions and orientations of transmitter and receiver, as well as the environment [1]. The sparsity means that it is easier to identify and track individual specular multipath components that can be used for high-precision positioning. The sparsity directly translates to an increased SINR of the individual components as the clutter from the diffuse part of the channel impulse response acts as interference. This tight connection between the radio channel and the propagation environment in 5G communication can thus be harnessed for the purpose of positioning. This is in stark contrast to conventional communication below 3 GHz, where the signal is richer in the number of important multipath components (with respect to the interference caused by the diffuse background clutter in the impulse response) and signals tend to arrive (and depart) from more directions, with less dependence on specific elements of the propagation environment. Moreover, at lower frequencies, fewer antennas can be packed in a given area, limiting the angular resolution. Nevertheless, signals below 3 GHz will also be part of 5G and can form a fallback positioning solution with possibly degraded performance when mm-wave signals are unavailable.

2) Large bandwidths: With the use of higher carrier frequencies comes the possibility of employing much larger bandwidths in 5G signals. It can be expected that 5G will use frequency channels with widths on the order of hundreds of MHz, largely exceeding the 20 MHz channels in LTE and the 100 MHz blocks available in LTE-A using carrier aggregation. The effect of a large bandwidth is two-fold: reduced latency due to shorter symbol times and increased accuracy of time-based measurements, due to finer delay resolution. The ability of 5G to deliver time-critical services, with end-to-end latencies less than 5 ms, is due, in part, to large bandwidths, which allow fast signaling and data transmission. Combined with advancements across the protocol stack and processing near base stations rather than in the cloud, ultra-fast communication and positioning create a mutual synergy. On the other hand, the effect of an increase in bandwidth also leads to a proportional improvement in time-delay estimation, which depends on the so-called effective bandwidth. Time-delay estimation translates directly to distance estimation through time-of-flight (TOF) and time-of-arrival (TOA) measurements, provided some form of synchronization between devices is achieved, either through TDOA measurements or through two-way packet transmissions. Preliminary studies have shown that errors on the order of a few centimeters can be achieved using a bandwidth of 100 MHz [2]. However, in order to achieve extreme ranging precision, other technological factors have to be considered, such as the imperfection of the internal clock-oscillator [3]. Not only the delay estimation accuracy increases with the bandwidth, but also the resolution improves. This refers to the ability to resolve closely spaced replicas of the signal produced by nearby reflecting objects or vehicles. The interference between two replicas does not affect the ranging estimation when their relative delay is greater than the inverse of the bandwidth, which for instance in the case of 300 MHz bandwidth corresponds to 1 meter. Since the distance between vehicles and other road elements is typically greater than this value, the delay of the LOS component as well as of reflectors can typically be estimated in a straightforward manner [4].

3) Large number of antennas: When a large number of antennas is available, near-pencil signal beams can be employed at either the transmitter and/or the receiver. On the one hand, beamforming can improve communication quality by allowing higher antenna gains for a link-budget increase and by reducing interference with directive communications. This also affects delay estimation accuracy, which does not only depend on the signal bandwidth, but also on the signal-to-noise ratio (SNR), the number of antennas, and the amount of multipath interference. Sufficient signal-to-interference-plus-noise ratio (SINR) gain will be available thanks to the use of directional antennas or beamforming with relatively large arrays, compounding the effect of increased bandwidth, and finally resulting in orders of magnitude of improvement in time-delay estimation accuracy compared to conventional cellular communications [4]. However, and especially at high carrier frequencies where the signal is received from fewer directions, a great challenge is the problem of beam alignment without which all the benefits of beamforming will vanish due to the lack of sufficient SNR to establish a link. For this reason, a great deal of research in 5G is devoted to the development of time-efficient beam training solutions [1]. On the other hand, it is well-known that the usage of large antenna arrays can drastically improve the accuracy of bearing/angle of arrival (AOA) estimation – the uncertainty on bearing estimation is inversely proportional to the SNR, the number of antennas, and the number of samples – and, subsequently, improve positioning quality. Preliminary studies at conventional cellular frequencies show that it is possible to reach centimeter level positioning accuracy with a bandwidth of 40 MHz when having many antennas at the base station [5].

4) D2D communication: D2D communication for vehicular communication is natively supported by IEEE 802.11p. In LTE release 14, V2X communication will be supported, in two complementary transmission modes: conventional network-based communication for interaction with the cloud, and direct D2D communication, for high-speed, high-density, low-latency communication. Similarly, 5G D2D communication will provide direct, ultra-fast and high-rate communication links between vehicles. This leads to improved coverage, improved spatial reuse, as well as high-rate, low-power connections. Similar to communication, D2D is also beneficial for disseminating and computing location information, using the so-called cooperative positioning paradigm. In cooperative positioning, devices collect measurements (e.g., distances, angles, relative velocities) not only with respect to reference stations (i.e., fixed access points), but also with respect to other mobile devices. These measurements can be utilized in cooperative algorithms to improve both the positioning coverage (i.e., the fraction of devices that can localize themselves) and accuracy. Moreover, cooperative positioning allows for relative positioning, even in the absence of reference stations. This is especially desirable for perception and planning tasks in vehicles, complementing existing on-board sensors. In 5G in particular, D2D communication can benefit from ultrashort latencies, allowing tracking of fast-moving devices such as vehicles, thus enhancing the recognition and the prediction of dangerous situations.

5) Network densification: A final property of 5G networks is network densification, with a hierarchy of base stations, associated with different cell sizes, and connected with high-speed back-haul links. In dense networks, devices can connect to a plurality of access nodes, which provides higher data rates with less energy consumption, under the condition that interference and mobility problems can be solved. If these challenges can be addressed and if access points can somehow announce their coordinates, ultra-dense networks can enable ultra-accurate positioning [3]. The reason is that positioning accuracy depends not only on the quality of the individual measurements (for which large bandwidths and many antennas are beneficial), but also the diversity and number of reference stations. Moreover, with very dense networks, there is a high probability of line-of-sight communication, and thus a strong signal directly related to the geometry between transmitter and receiver. In summary, 5G network densification can help in supporting vehicular positioning to the accuracy levels listed in Fig. 1

III. Recent Progress: Models, Designs, and Methods

Now we have established that 5G is promising for positioning, we will provide a brief overview of recent progress in this area. Our focus will not be on providing novel results, but rather on trying to connect together different aspects of 5G technology from a positioning standpoint, which are usually scattered in the literature. Some of these works do not explicitly consider vehicles, but rather general-purpose positioning. Therefore, in Section IV, we will highlight specific challenges for 5G positioning for vehicular applications.

A. Channel Modeling and Waveform Design

When using channel models for evaluation of positioning performance it is important that geometrical information is included in the model. A pure stochastic description of the channel and its properties is typically not desirable, as it does not contain any relation between channel contributions. There are two groups of models that inherently contain position information: ray-tracing models and geometry based stochastic channel models (GSCMs). Ray-tracing models are used when the environment is known and well described in a 3D map. The problem for radio based positioning using ray-tracing is that the propagation models and environment maps are not always developed with a positioning perspective in mind and that fine details of the environment are neglected in the 3D maps. GSCMs can be seen as a simplified form of ray-tracing, but in a virtual map where scatterers are placed randomly according to statistical distributions. Such a map is a way to geometrically represent the scattering interaction. For V2V communication, the virtual map may try to resemble a realistic street layout to enforce scatterers where they are typically found, e.g., in street intersections, along walls and at building corners, with scattered contributions from streetlights, traffic signs etc. In [6], a GSCM for a highway scenario is presented. The contributions from scatterers are divided into the following groups: mobile discrete, static discrete, and diffuse. The static discrete scatterers are the primary signal components to use for absolute positioning in the environment. The line-of-sight component between vehicles together with contributions from discrete scatterers are useful for relative positioning, whereas diffuse scattering acts as noise from a positioning point of view, and deteriorates the positioning performance [4]. In [7], the scattering behavior for V2V communication is analyzed in detail for urban intersections and highway scenarios. The measurements show that, with sufficiently large bandwidth, there are typically 10–20 multipath components that can be tracked and used for positioning. The lifetime of these multipath components varies, which of course is a challenge for positioning, in the range from a few meters to hundreds of meters. In highway traffic where two vehicles are approaching each other, 50% of the multipath components had a lifetime exceeding 50 m.

Communication over the mm-wave channel, modeled through GSCMs, forces the designer to take certain practical aspects into consideration. In contrast to systems below 3 GHz, the large number antennas at both transmitter and receiver in 5G today preclude the use of an RF chain for each antenna element, for reasons of cost and power consumption. This has led to a shift from all-digital transceivers to hybrid models, with analog or hybrid beamforming techniques. Consequently, the receiver does not have access to the full analog received waveform, requiring modifications for both positioning and communication-related signal processing [1]. Within the limitations of the transceivers, waveforms can be optimized for positioning purposes [8], e.g., to exhibit impulse-like autocorrelation if a large bandwidth is available [4].

B. Performance Bounds

Given a certain channel model, transceiver architecture, and signal structure, communication and positioning will treat the received signals from different viewpoints. Useful tools to guide positioning algorithm and system design are, e.g., fundamental performance bounds, which relate the quality of the positioning with the statistics of received waveforms, generally through intermediate variables, such as the TOF and AOA. A common approach is the computation of the Fisher information matrix (FIM) and the related Cramér-Rao bound (CRB).

Recent works revealed that, when using large bandwidths, AOA measurements obtained by wideband antenna arrays do not further improve position accuracy beyond that provided by TOA measurements at each antenna element, even though, from a practical perspective, separate TOA and AOA estimation still remains the most pragmatic approach [9]. In dynamic scenarios, like the vehicular one, also the measurements of the Doppler shifts, if properly exploited, provides additional Fisher information, with intensity determined by the vehicle's velocity and the root mean square signal duration [9].

While the above general statements apply to all wideband communication systems, dedicated 5G analyses have also been conducted [10]–[12]. A single-antenna perspective was taking in [10], focusing on the impact of network densification and cooperative positioning. In [11], the determination of position and orientation of a device based on beams from a single base station was considered, while in [12] a comparison between single-link positioning using either beamforming or MIMO indicates that on average, better accuracy can be achieved with MIMO, at expense of much higher complexity. Thus, with the ability to estimate both distances and angles, positioning using a single infrastructure node becomes possible, which will reduce requirements on the positioning algorithms. Moreover, neighboring vehicles could find their relative position through pairwise interactions, thus avoiding the need of multi-lateration with multiple vehicles or with infrastructure (which might not even be present).

To illustrate the fundamental performance behavior of 5G positioning and the impact of beam-misalignment, we consider a scenario with a vehicle circling an access point, at a distance of 20 m. The vehicle and access point use uniform linear array (ULA) antennas to generate 2 beams with fixed direction, i.e., one beam is pointing to the boresight direction and the other is shifted by 0.001 radians. The transmit power is 27 dBm and the bandwidth is 100 MHz. Initially, the vehicle and access point are facing each other with beams perfectly aligned (0 degree beam misalignment). As the vehicle moves along its circular trajectory, the beams from the access point will become misaligned, resulting not only in a reduction of the SNR, but also the positioning quality, here shown as the position error bound (PEB), which is defined as the square root of the CRB on the position, expressed in meters. Fig. 4 shows the PEB as a function of the amount of beam misalignment. We notice that increasing the number of antennas, thus reducing the beam-width,[1] can significantly reduce the localization error when beams are perfectly aligned. When the beam direction is erroneous, the positioning performance quickly degrades. We can also notice the presence of periodic peaks that occur when the transmitter is pointing to a null direction of the channel response or a receiver beam. Clearly, the narrower the beam, the higher is the repetition of these peaks and the more severe is their impact. From the above, we see the need of beam-tracking to preserve a given positioning accuracy.

[1]The antenna beam-pattern follows the classic text-book model of ULA with beam-width and interspace between null directions inversely proportional to the number of antennas.

C. Positioning and Tracking Algorithms

Up to this point, we have argued that 5G technologies are very suitable for providing extremely accurate measurements for position and orientation estimation with very low latency. These measurements should be integrated into the overall positioning and perception system from Fig. 2, through sensor fusion and filtering techniques. Moreover, the availability of very accurate range and orientation measurements provided by 5G signals, even it is sporadic, can be a key component for the calibration of other sensors. In addition, to enable cooperative positioning, cooperative algorithms together with communication approaches with different of levels of centralized vs. distributed computation must be considered. These approaches can themselves rely on 5G signals, but can also be based on a combination of 3G and 4G, or IEEE 802.11p.

Recent activity in this area has highlighted some interesting directions, in line with the findings from Section III-B. For instance, the need of having several reference points, and consequently the use of one form or another of triangulation algorithm, may be eliminated. In fact, the determination of the position and the orientation using only one access point may be possible. In [3], tracking was performed using extended Kalman filters in two stages: a local tracker at each base station for the AOA and TOA, followed by a global tracker of the user position. The same work accounted also for time-varying clock parameters, and through high-fidelity simulation, demonstrated localization and tracking with uncertainties of less than one meter in the 3.5 GHz band. In [4] indoor positioning of a device using a single reference device was proposed, by exploiting multipath information in the wideband 5G waveform. The fact that few reference devices are needed was also observed in [13], which conducted an evaluation of the performance of different measurements under LOS and NLOS, also exploiting signal reflections. Finally, the flexibility of using multiple antennas jointly with wideband signals in the mm-wave band and sparse signal-processing (compressive and sparse sensing) has been considered for channel parameter estimation, where angles and delays can be estimated jointly [14].

IV. Challenges and Opportunities

The use of 5G signals and system properties for general-purpose positioning is currently being investigated. Nevertheless, vehicular applications bring a number of specific challenges, some of which we point out here.

- Mm-wave signals and signals below 6 GHz each have distinct benefits and drawbacks for positioning. As 5G systems will likely use both signal types, the study of the quantitative performance gains and complexity/performance trade-offs is needed. Dedicated tracking algorithms, as in [3] for sub-6

GHz frequencies, which can optimally combine both types of signals, can offer significant benefits compared to using only one technology.

- There is an opportunity of information fusion of measurements from heterogeneous sensors (e.g., inertial, camera, other wireless signals), through suitably designed tracking filters, with specific demands in high-speed processing and calibration. In addition, cooperative positioning methods need to be adapted to the vehicular scenario, with high mobility and time-varying networks. Both network-centric and device-centric positioning are to be investigated, in terms of the achievable performance and cost. Device-centric positioning has a value for relative positioning, when no infrastructure is available, or when latency is critical.
- 5G presents a strong synergy between communication and positioning, with unique trade-offs in terms of data rate and positioning accuracy that should be explored. These synergies are relevant both at the protocol level (the fact that beamforming can benefit from position information and positioning relies on beamforming), but also in terms of fundamental properties, such as Shannon capacity and Fisher information. These properties must then be translated into design guidelines in terms of frame structure, reference signals in uplink and downlink, precoder design, channel estimation, etc.
- Due to inherent mobility, positioning and communication must occur at extremely short timescales. While ultra-fast communication is an active topic in 5G, ultra-fast positioning is still under-explored, especially in light of high vehicle density and rapidly changing network topologies. Dedicated waveforms and beamforming protocols can support progress in this area.
- Positioning quality tends to be better for geometrical configurations over a large area, with large angular separation between reference nodes. In contrast, vehicles tend to be in one-dimensional configurations, reducing the accuracy of cooperative localization schemes. To this end, multipath reflections can be exploited to improve positioning and even to obtain a position fix in the absence of a LOS path. In addition, favorable vehicle topologies and formation driving schemes would significantly improve positioning and tracking performance.
- Due to the large size of a vehicle with respect to the antenna, the embedding of multiple antenna arrays will be possible for each vehicle. Signals between such arrays need to be processed and synchronized accordingly, both for communication and positioning.
- Mm-wave technology is already present in vehicles in the form of anti-collision radars working at 77 GHz, capable of detecting close obstacles and performing high-precision ranging. In combination with 5G, such a technology could also be used to enhance the radar capability of cars toward 3D automatic mapping, but with reduced cost and without mechanical steering devices, compared to

lidar. Such an idea has been recently investigated in the field of indoor automatic mapping [15]. This technology could be fused with other sensors to increase the reliability of autonomous-driving vehicles or to assist the driver in avoiding obstacles, as shown in Fig. 5.

- The realization of large antenna arrays and associated RF front-ends poses several challenges. For instance, phase shifters are generally based on simple RF switches that generate serious quantization effects during the beamforming process, which leads to radiation pattern distortion and squinting effects (frequency distortion) that could impact the localization accuracy [12], [15]. Novel front-ends and tailored processing have to be designed to compensate for these effects.

V. Conclusions

Accurate positioning of vehicles will rely on a combination of sensors. For the first time, mobile communication technology in the form of 5G can become one of those sensors. This is due to the unique combination of five properties that are favorable for accurate positioning: high carrier frequencies, large bandwidths, large antenna arrays, device-to-device communication, and ultra-dense networking. Together, these properties create an ecosystem for ultra-accurate positioning and mapping of vehicles, other road users, and the traffic environment. We presented recent research in this area and have highlighted several promising research directions.

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Fig. 1. According to the 5G Automotive Vision of 5G-PPP, applications require positioning accuracies from more than one meter to below 10 centimeters. The table shows different technologies, their ability to meet the requirements, as well as comments regarding their cost, latency, and reliability.

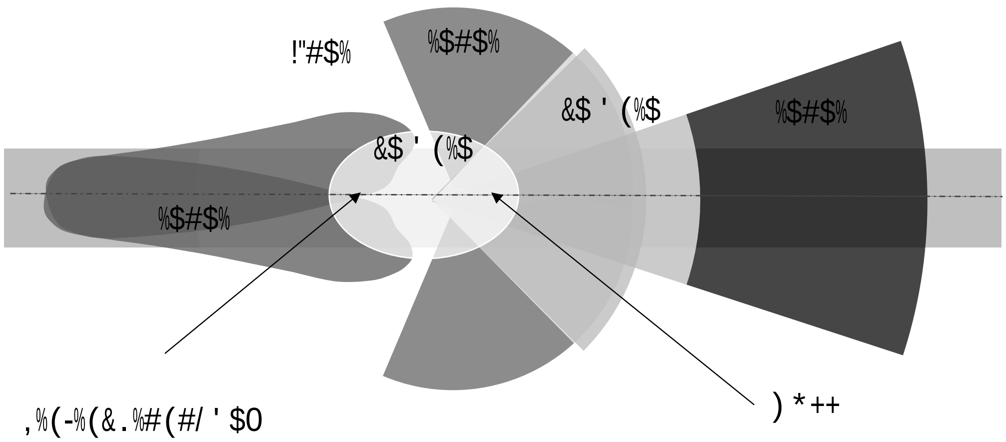

Fig. 2. Main positioning technologies for automotive applications. In addition to signals from GNSS satellites, a variety of relative positioning technologies (with indications of their relative range) are available. These can be combined with a pre-recorded map to provide accurate absolute positioning.

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Position error	> 100 m	> 50 m	< 50 m	< 10 cm*
Orientation error	N/A	N/A	N/A	< 1 degree*
Latency	> 1 s	> 1 s	> 1s	<< 1 s*

*Potential performance

Fig. 3. Different generations of cellular communication systems have always provided coarse position information. 5G will be able to provide accuracy position information, useful for vehicular applications.

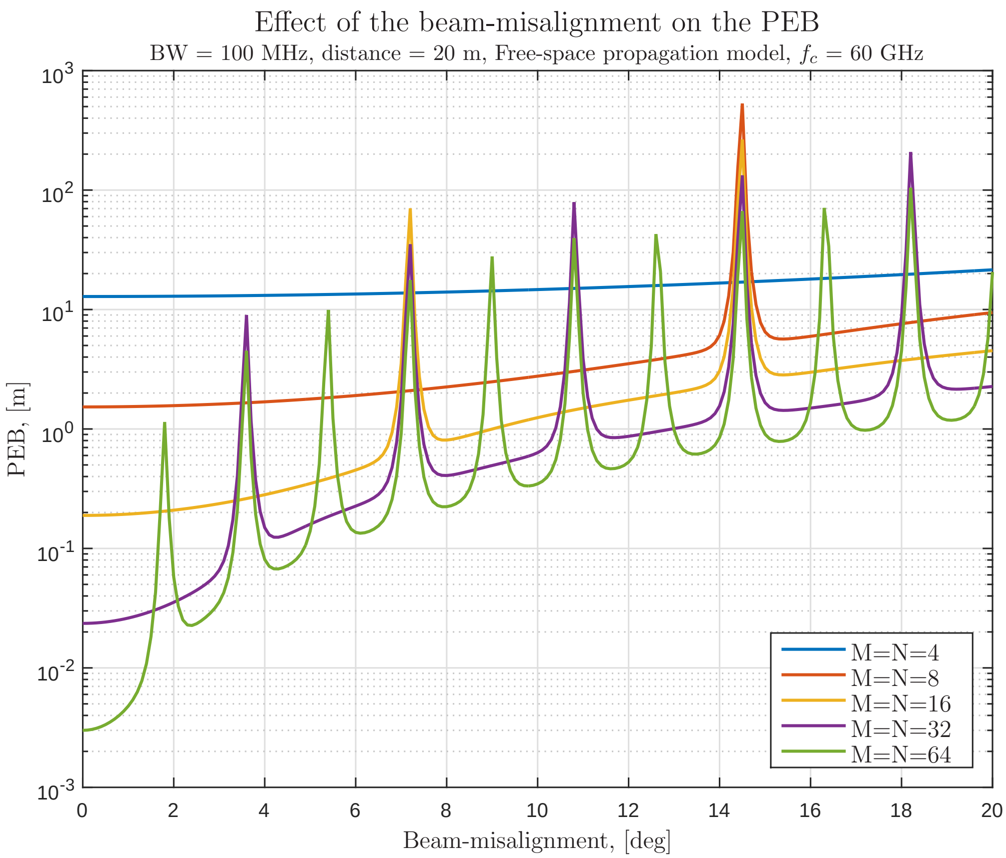

Fig. 4. Positioning performance (PEB, indicating the positioning accuracy that can be achieved) of a vehicle for different number of transmit antennas N and receive antennas M, using a 100 MHz signal centered around at 60 GHz carrier from a single reference station. The figure shows that with more antennas, positioning accuracy improves, but becomes more sensitive to beam misalignment, which here is modeled by the receiver moving outside of the directions of the beams.

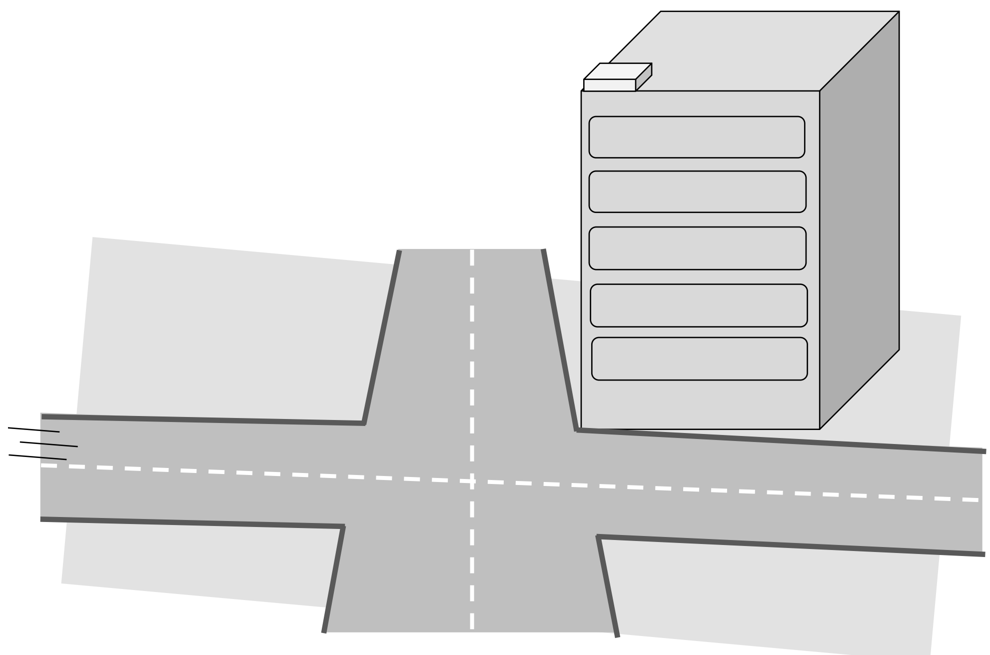

Fig. 5. 5G will provide accurate positioning for individual vehicles and can also support mapping of the environment as well as discovery of vulnerable road users.