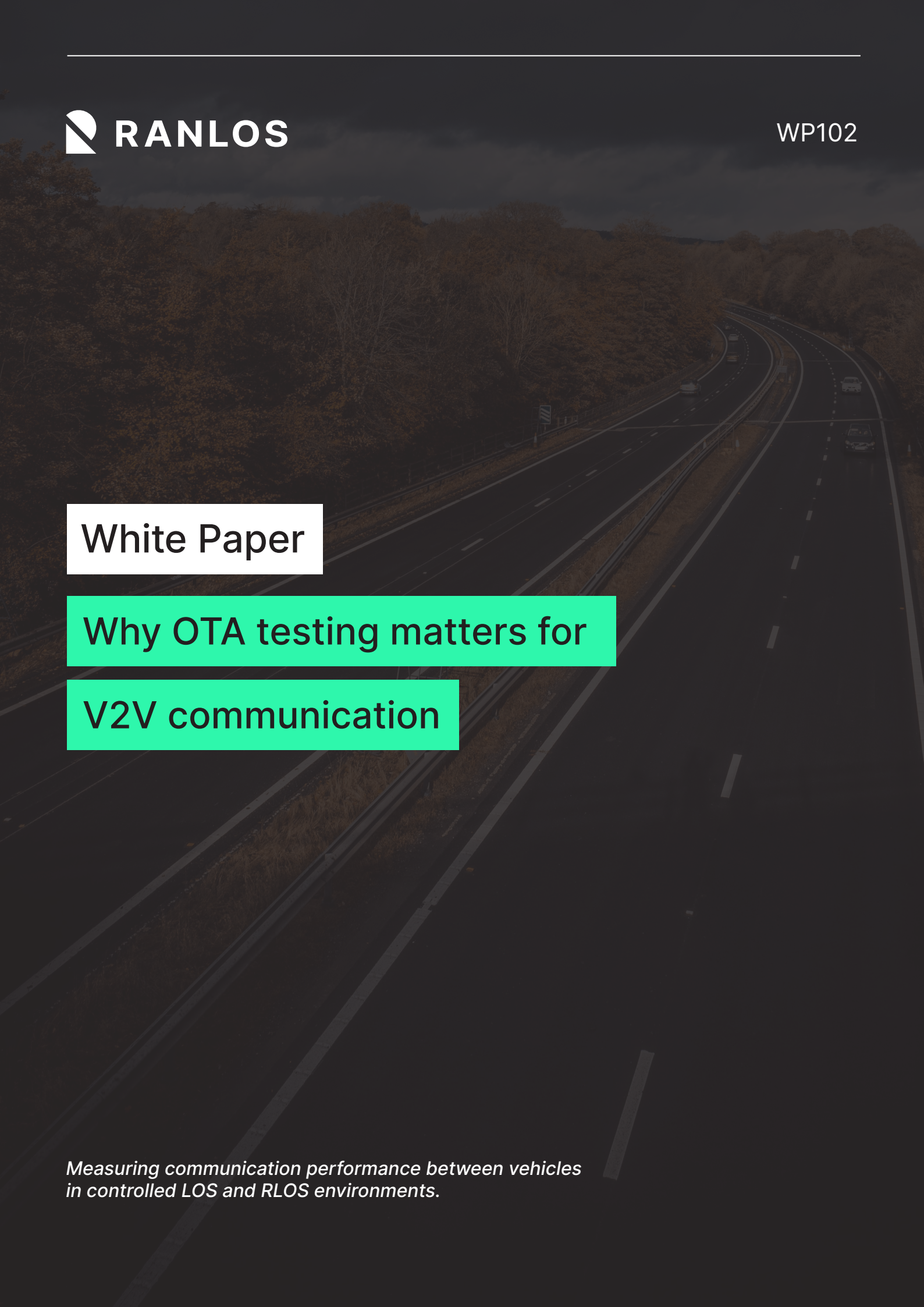
RANLOS

WP102



White Paper

Why OTA testing matters for V2V communication

Measuring communication performance between vehicles in controlled LOS and RLOS environments.

Introduction: Why OTA testing matters for V2V communication

Wireless communication is becoming an increasingly important part of modern vehicles. Vehicle-to-Vehicle (V2V) communication enables cars to exchange real-time data about position, speed and driving conditions, including safety-critical messages that help prevent collisions and support cooperative driving. V2V is one part of the broader Vehicle-to-Everything (V2X) ecosystem, which extends to communication with infrastructure, networks and other road users. What all these applications have in common is a requirement that cannot fail: a stable and reliable wireless communication link.

Traditional measurement methods, where antennas and radio components are tested separately, often with the antenna measured in isolation in an anechoic chamber, provide valuable insights but do not capture how the complete system behaves during real operation. Once the antenna is integrated into the vehicle, its performance is influenced by the body shape, material selection and nearby components. As a result, actual radio performance often differs from what was theoretically expected. This is where OTA testing (Over-The-Air) becomes essential: by testing the complete, integrated system in a controlled radio environment, it becomes possible to measure how communication actually performs.

At the same time, vehicles do not operate in a single, uniform radio environment. Two vehicles approaching each other on a highway or at a rural intersection communicate via a link dominated by a direct signal path, known as a LOS environment (Line-of-Sight). In dense urban traffic, a vehicle is surrounded by reflections from buildings and other vehicles. This is approximated in testing by a RIMP (Rich Isotropic Multipath) environment – a standardized reference case where signals arrive equally from all directions. LOS and RIMP represent opposite ends of the spectrum, and each reveals different characteristics of a system's performance.

For V2V communication specifically, there is an additional factor: the relative angle between vehicles is constantly changing. One may approach head-on, cross from the side or overtake from behind. It is this continuous shift in geometry, and not just the environment itself, that makes V2V one of the more demanding wireless applications to test correctly. The RLOS model (Random Line-of-Sight) is designed to capture exactly this.

Fact box: definitions and terminology

- **V2V (Vehicle-to-Vehicle):** wireless communication directly between two vehicles, typically at 5.9 GHz via DSRC/ITS-G5 or C-V2X (two competing but compatible technology standards for connected vehicles).
- **LOS (Line-of-Sight):** a radio environment where the direct signal path dominates – no significant reflections. Typical on open roads and highways.
- **RLOS (Random Line-of-Sight):** a statistical model for LOS environments where the signal channel is stable, but the angle between vehicles changes continuously. The 'random' refers to variation in geometry, not in the measurement.
- **RIMP (Rich Isotropic Multipath):** a radio environment where signals arrive from many directions due to reflections and scattering – typical of cities, tunnels and parking structures.
- **RanLOS:** used in this document exclusively as the name of the company and its test systems, which realize a LOS environment.

Two complementary radio environments

Research conducted at Chalmers University of Technology by Professor Per-Simon Kildal and colleagues (Carlsson, Carlberg & Kildal, LAPC 2012; Kildal & Carlsson, 2013) established a theoretical framework for OTA testing based on two reference environments: RIMP and LOS. These represent two extremes in how radio waves behave. Although real-world scenarios often fall somewhere between them, this distinction makes it possible to analyze different aspects of wireless system performance in a structured way.

LOS – Line-of-Sight (RLOS model)

In a LOS environment, communication is dominated by the direct signal path between transmitter and receiver. This is the typical situation on highways, rural roads and in many intersection scenarios – exactly the conditions that characterize most safety-critical V2V exchanges. Unlike environments with many reflections, there is no alternative signal path here that can compensate for weak antenna coverage in a given direction. The antenna's behavior in each individual direction directly affects what the receiver picks up.

For V2V, a static LOS model is not sufficient on its own. The angle between vehicles changes continuously during real operation – they approach head-on, cross at intersections, or one overtakes the other. The RLOS model captures this: rather than testing performance at a single fixed angle, RLOS analysis describes how the system performs across the full range of real-world geometries it will encounter. In a multipath environment, signal variations tend to average out across many directions. In a RLOS environment, no such averaging takes place – a direction with low antenna gain is a direction where communication may fail.

What LOS/RLOS measurements reveal

LOS/RLOS-based measurements provide a direct picture of how antenna behavior influences the communication link and are used to analyze:

- Antenna coverage across the full horizontal plane and 3D sphere
- Polarization alignment between the antennas of the two vehicles
- Link budget and maximum communication distance
- The occurrence of nulls and blind spots – directions where the link weakens or fails
- The gain from using multiple antennas at different positions on the vehicle

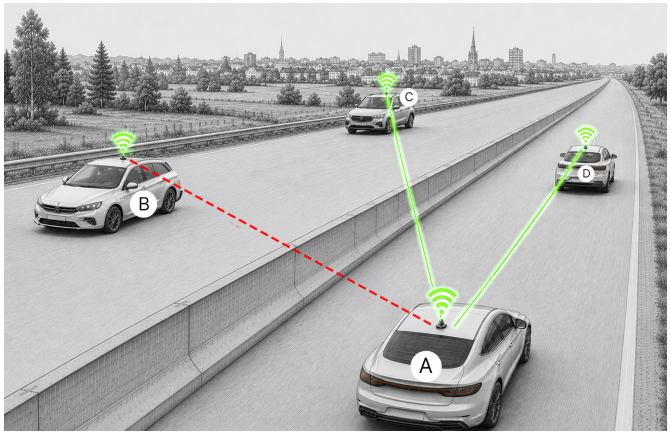


Figure 1: If the antenna radiation pattern on the vehicle A is weak of the direction of vehicle B there will be bad or insufficient connection.

What LOS/RLOS measurements reveal

Since there is only one signal path in a LOS environment, antenna behavior has a direct impact in every orientation. If the roof antenna has uneven coverage, low-gain directions or poor alignment relative to the other vehicle, signal quality in certain approach angles may drop too low – even when the link works well in other directions. In practice, this can appear as:

- Intermittent link failures as vehicles change relative position
- Signal strength that varies depending on approach direction
- Limitations in the range at which a stable link can be maintained

This is particularly critical when a safety message must get through on the first attempt – a collision warning that arrives too late has no value.

RIMP – Rich Isotropic Multipath

In a RIMP environment, radio waves arrive at the receiving antenna from all directions with statistically equal probability. Signals are reflected, scattered and diffracted by surrounding objects – buildings, vehicles and vegetation – creating a dense, statistically uniform field of incoming signals. This is the typical radio environment in crowded cities, tunnels and parking structures.

An important characteristic of RIMP is that variations related to antenna directional properties are largely averaged out by the surrounding reflections. An antenna with uneven coverage can still perform consistently, because signals always reach the receiver through alternative paths. For V2V scenarios that largely take place under open line-of-sight conditions, this means that critical weaknesses – such as low-gain directions – may remain hidden during RIMP testing, even though they can be decisive in real operation.

What RIMP measurements reveal

RIMP measurements provide insight into how a system performs in complex radio environments dominated by multipath propagation and are used to analyze:

- Total radiation efficiency – how much of the transmitted power actually reaches the receiver, and vice versa
- Antenna correlation and the possibility of efficient diversity combining
- MIMO performance – using multiple antennas to improve data throughput and reliability
- The occurrence of signal fading and how well the system handles it
- Unwanted coupling between antennas in multi-antenna systems

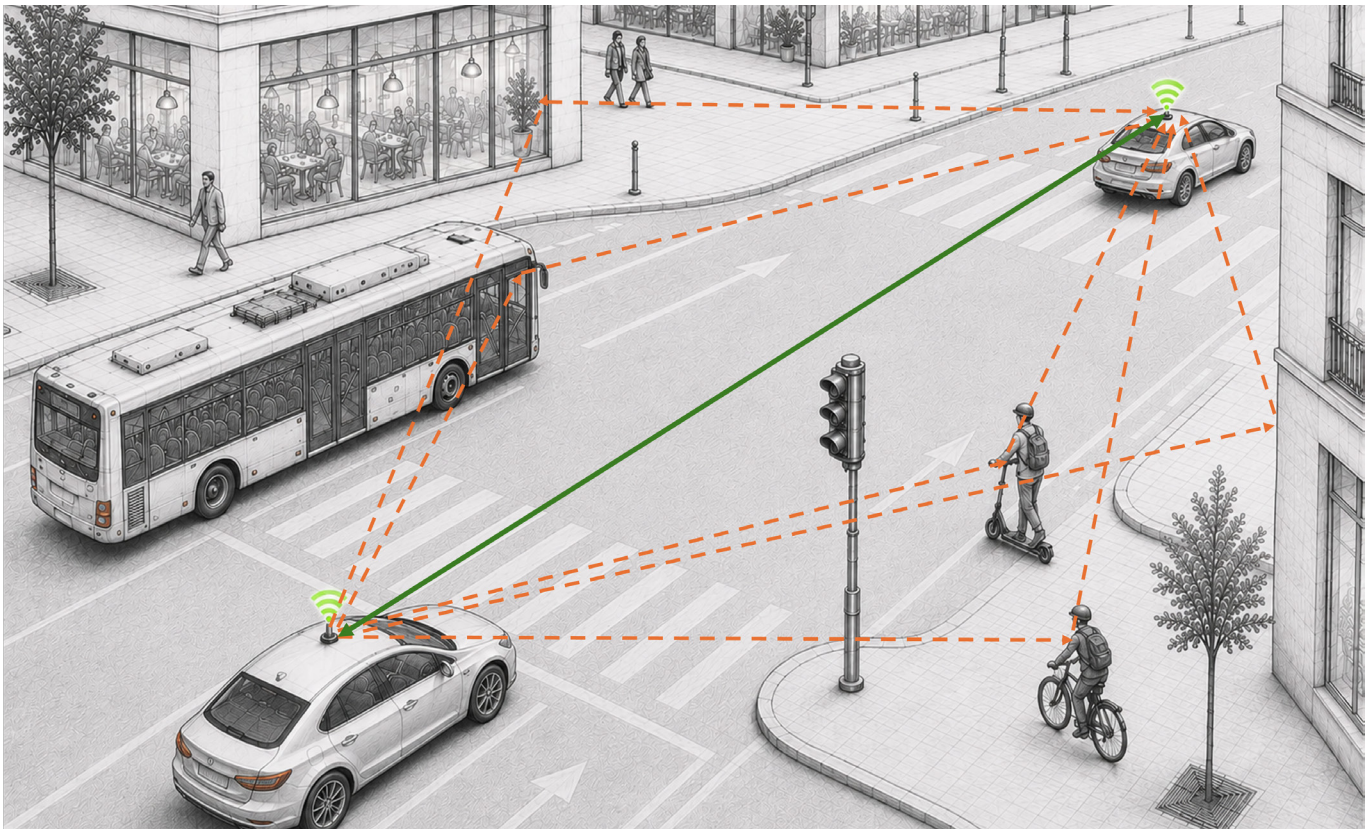


Figure 2: Urban environments create multiple reflected V2V signal paths from buildings, vehicles and infrastructure. The direct LOS path is shown in green, while orange dashed paths illustrate multipath components that reach the receiving vehicle through surrounding reflecting surfaces.

Measuring V2V communication performance

Performance metrics

Communication performance is commonly evaluated through parameters such as Received Signal Strength Indicator (RSSI), Packet Error Rate (PER), throughput and diversity gain. Among these, PER – the share of messages that fail to arrive correctly – is the most direct measure of reliability. V2V systems often exhibit sharp threshold behavior: as the received signal drops toward the receiver's minimum sensitivity, packet loss can go from near zero to near 100 % within only 1–2 dB of signal change. Very small differences in antenna performance can therefore determine whether a safety message is received or lost.

Lessons from practical measurements

Experimental work carried out at RanLOS (Westerlund, 2025) investigated communication performance between two V2V nodes using commercial hardware. The study demonstrated the importance of antenna placement and diversity. Two antennas at different positions on the vehicle roof complemented each other depending on the approach direction – a direct illustration of the RLOS effect. The most striking finding was the sharpness of the communication threshold: packet loss went from near zero to near complete within only 1–2 dB of signal variation.

Initial measurements were performed in a parking lot, which revealed three key limitations: uncontrolled reflections from nearby structures, only two vehicle approach angles available, and insufficient precision to map the sharp PER transition. These observations pointed directly to the need for a controlled setup.

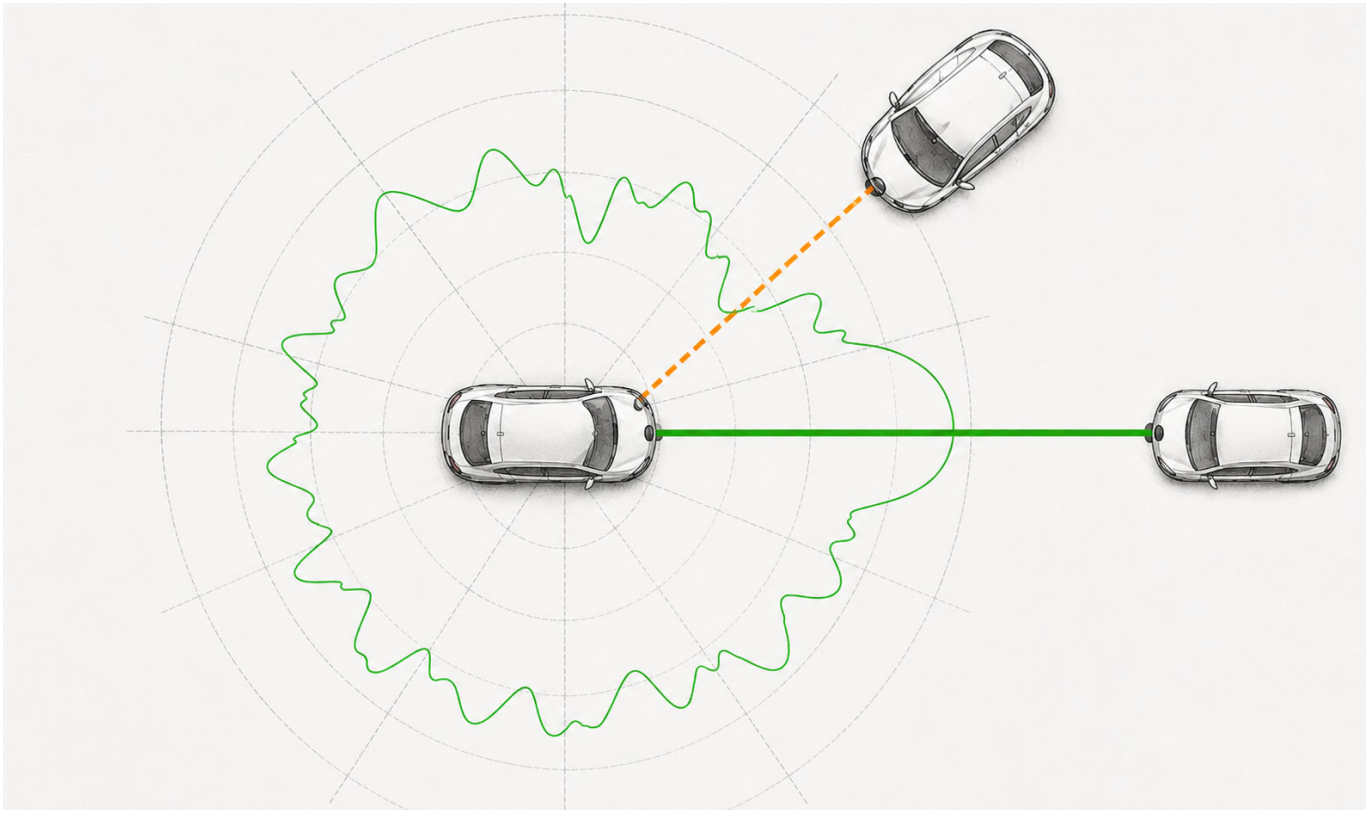


Figure 3: V2V communication performance depends on the antenna radiation pattern around the vehicle. Peaks and dips in the pattern can create strong or weak link directions depending on the relative position of the vehicles. Near the receiver sensitivity threshold, even small changes in received signal strength can cause a sharp increase in packet error rate.

Measurement setup

The core principle of the RanLOS approach is that real, commercial V2V nodes are used as communication endpoints – while the RanLOS system controls the wireless channel through which they communicate. The setup combines the following:

- RanLOS BeamForce (antenna array + reflector) – acts as the signal source. The signal from the transmitting V2V node is fed into the array, which via the reflector creates a plane wave – a clean, focused signal from a defined direction – in the test zone. The vehicle sees a signal as if it came from a distant vehicle at a precisely defined bearing.
- External V2V nodes (e.g. Autotalks CRATON) – the actual communication endpoints. The transmitting node generates real V2V traffic; the receiving node, mounted on the vehicle with its real roof antennas, is the device under test.
- Turntable/positioner – rotates the vehicle step by step through the full horizontal plane and, with a positioner, also vertically. This maps the communication link across all possible approach angles and reveals nulls and blind spots.
- Programmable attenuator (0.25 dB resolution, software-controlled) – sets the effective signal strength precisely and repeatably, without touching cables or antennas. This directly addresses the limitation of the parking lot study and makes it possible to map the sharp PER threshold point by point.
- Measurement instruments – antenna calibration is verified before testing; the nodes' own logging provides per-antenna signal strength and packet data at each measurement point.

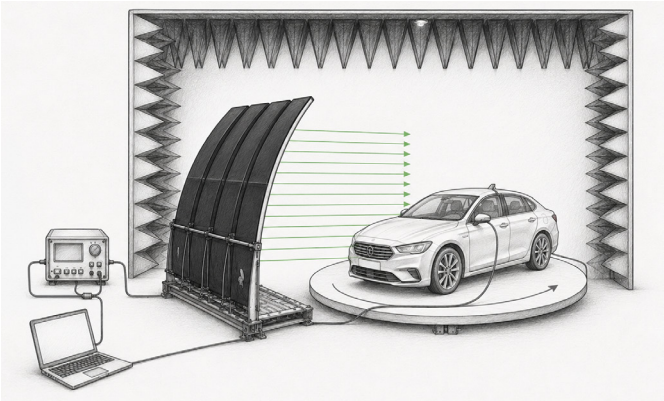


Figure 4: Controlled V2V performance measurements can be created in a lab setup using an a V2V signal source, programmable attenuator, a RanLOS BeamForce system and a vehicle under test on a rotating platform inside a semi-anechoic chamber. The setup enables repeatable measurements of RSSI, PER and link performance across vehicle orientation. The RanLOS BeamForce test system generates a controlled plane wave toward the vehicle, while BeamLab controls the measurement sequence and logs performance metrics such as RSSI and PER.

What LOS/RLOS testing captures for V2V

RanLOS testing focuses on the parameters that are often directly connected to real-world communication issues:

- How the roof antenna covers different vehicle approach directions
- Where there is a risk of low signal levels – blind spots that can cause intermittent failures
- At what signal level packet loss begins to rise sharply
- How much improvement multiple antenna positions provide
- What maximum communication range can be expected under realistic conditions

In many cases, these are precisely the factors that determine whether a V2V system performs reliably or not – and they are most clearly visible in a controlled LOS environment.

"To develop and verify V2V systems, test methods must reflect the radio environments in which the systems are actually intended to operate."

Standardization and regulatory relevance

OTA testing of V2V systems is an active area within standardization. In Europe, ITS-G5 established the initial framework for direct vehicle communication at 5.9 GHz, while C-V2X – covering both LTE-V2X and the 5G generation NR-V2X – has emerged as the prevailing direction globally.

Today, standardization efforts reflect a consistent expectation: testing must capture the environments where systems actually operate. For V2V safety communication, that means line-of-sight (LOS) scenarios on open roads, at intersections and on highways – the conditions where safety-critical messages must not fail. Testing system performance under those conditions, rather than verifying protocol conformance alone, will be increasingly important moving forward.

On the assessment side, Euro NCAP has introduced a Connected Safety Reward programme recognising vehicles equipped with V2X cooperative safety functions, and its 2026 protocol restructuring places connected driving functions within the scored assessment categories. In China, C-V2X is embedded in national automotive policy through the MIIT Technology Road Map 2.0, alongisde upcoming certification programs.

The direction across markets is consistent: wireless performance is moving from a product feature toward a verified requirement. Companies that build test capability now are better positioned to meet those requirements as they are confirmed.

Conclusion

V2V communication places unique demands on wireless system performance. Safety-critical messages must get through reliably – under continuously changing vehicle orientations, at varying distances and without a second chance. As this paper has shown, the difference between a system that performs and one that fails can be as little as 1–2 dB of received signal variation.

The scenarios that matter most for V2V performance – highway driving, rural roads, approaching intersections, long-range cooperative driving – are dominated by direct line-of-sight conditions. In these situations, the angle between communicating vehicles changes continuously: approaching head-on, crossing paths at an intersection, overtaking on a motorway. The RLOS model captures exactly this – the full range of antenna angles a real deployment will encounter, without multipath to mask weak directions. These are the conditions where performance margins are thinnest, and where controlled LOS/RLOS testing reveals what matters.

Controlled LOS/RLOS testing enables the development decisions that matter: identifying coverage nulls before they become field problems, quantifying how much diversity gain different antenna placements actually provide, and understanding at what signal level the communication link becomes unreliable. These are the answers that antenna engineers, system integrators and OEM development teams need – and they are most clearly obtained in a controlled, repeatable LOS environment, at a stage when changes are still practical.

The critical question is not whether the system works under ideal test conditions – but whether it works when it matters most. That is the question LOS/RLOS-based testing, realized through RanLOS test systems, is designed to answer.

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