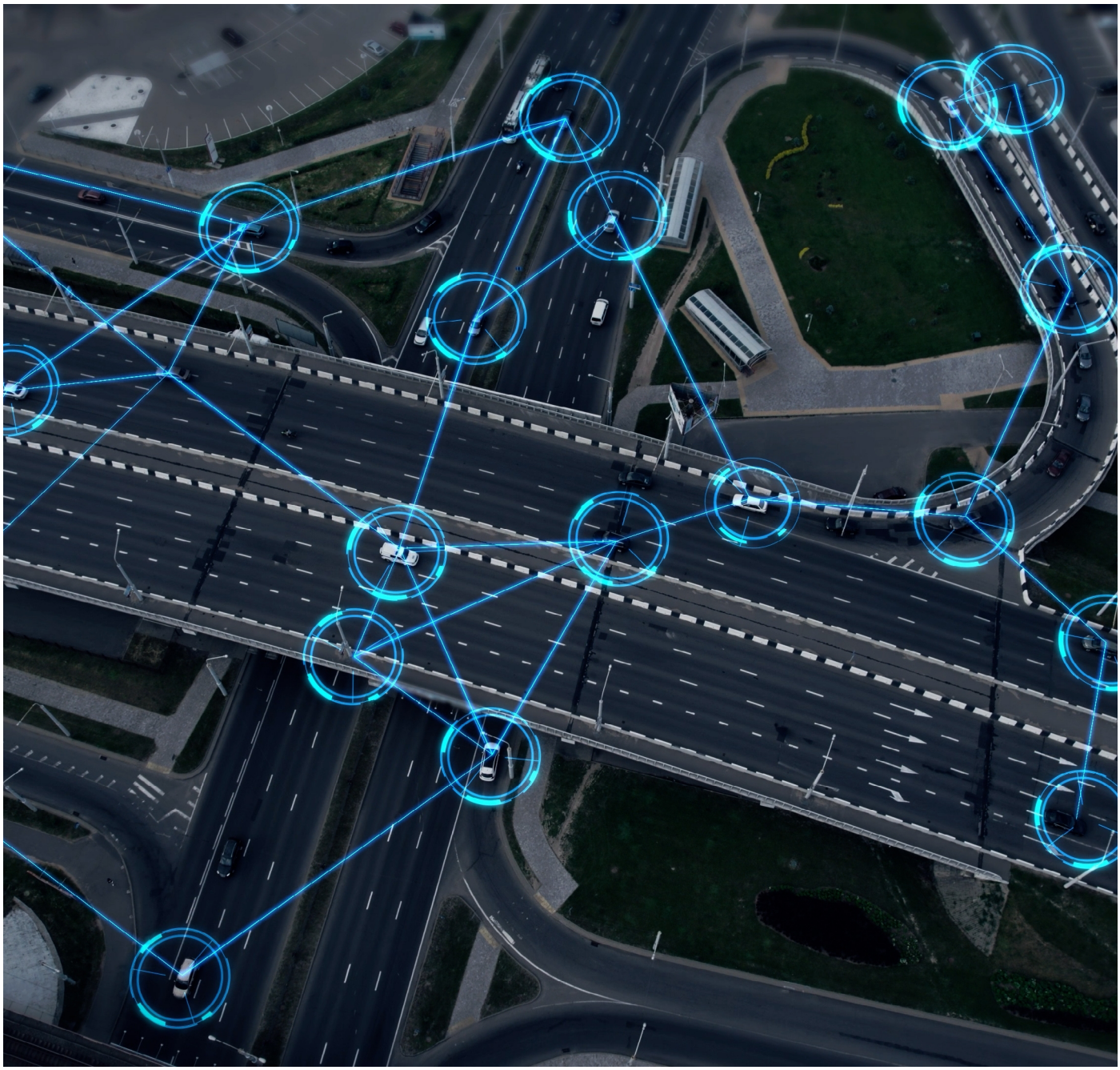
WHITE PAPER

ANTENNA TECHNOLOGY IN CONNECTED VEHICLES

Explore vehicle connectivity, its benefits, key considerations for antenna placement and the future of antennas in connected vehicles.



Antenna technology plays a critical role in intelligent transportation systems. As smart cities and Internet of Things (IoT) ecosystems evolve, antennas enable connectivity and support consistent RF performance between vehicles, infrastructure, and passengers. Today, antennas are used to support real-time traffic management, vehicle-to-vehicle communication, and passenger productivity. The integration of high-performance components has improved the efficiency and safety of transportation while helping to enable a more connected passenger experience.

EVOLUTION OF CONNECTED TRANSPORTATION



Antenna technology has made significant advances since its early days in the transportation sector. The transportation industry has undergone significant digital transformation over the past decade. Vehicles and transportation systems that once relied primarily on standalone communication technologies are now part of broader connected ecosystems that continuously exchange operational and environmental data. With this advancement, antennas now serve a broad range of applications including data collection and safety systems.

There has been a significant move toward smaller, more compact antennas. With space at a premium on transit platforms, antennas must be both efficient and unobtrusive, leading to designs integrated into the vehicle. Furthermore, the move toward multi-band and multi-port antennas allows systems to operate simultaneously on multiple frequency bands, maximizing the potential of cellular and Wi-Fi technologies to achieve the high data throughput required to serve multiple users.

CONNECTIVITY CHALLENGES IN SMART TRANSPORTATION

Increasing Data Demands

Applications like video streaming and telematics require high data throughput, placing pressure on antenna systems to support multi-band performance while minimizing interference.

Demanding Operating Environments

Components must be designed to help support operation in environments involving vibration, moisture, and temperature extremes.

Space Constraints

Modern platforms prioritize aerodynamics, requiring low-profile antenna designs that do not compromise performance.

TYPES OF ANTENNAS USED IN CONNECTED VEHICLES

A variety of antenna components are used in connected vehicle environments, with selection typically based on system requirements, installation constraints and operating conditions.



Omnidirectional Antennas

- Designed to transmit and receive electromagnetic signal across a broad coverage area
- Well suited for applications requiring a wide coverage area
- Commonly used for passenger connectivity and data transmission



Directional Antennas

- Designed to focus radiation patterns in a specific direction
- Well suited for applications requiring a more focused electromagnetic signal
- Commonly used in GPS/GNSS for satellite communications



Interior Wireless Antennas

- Intended to distribute RF coverage around the interior of a vehicle
- Likely omnidirectional and typically feature a narrower radiation beamwidth
- Designed for interior applications and generally less rugged than antennas intended for exterior use

ANTENNA PLACEMENT AND RF CONSIDERATIONS

Antenna placement is critical to their effectiveness in connected transportation. Improper antenna placement or installation can result in weak or degraded radiation performance.

Ground Plane: Vehicle antennas are typically designed for roof mounting, where the metallic surface serves as a ground plane. This conductive surface acts as a reference for the antenna's signal, playing a vital role in shaping radiation patterns and supporting efficiency. Modern panoramic or glass roofs reduce the available ground plane, making careful placement critical to maintaining consistent RF performance.

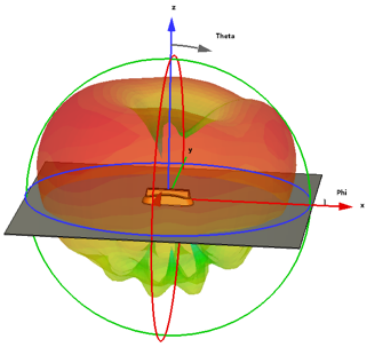
Roof Curvature: Curvature can tilt the radiation pattern and affect signal performance. It also presents a mounting challenge where gaps can cause water ingress and corrosion; therefore, antennas are often designed to accommodate the specific angle and shape of the roof.

Isolation and MIMO Performance: When several antennas are installed in close proximity, it can result in reduced isolation and high mutual coupling. This impacts MIMO (multiple-input, multiple-output) effectiveness by increasing spatial correlation between elements, which limits independent data streams and achievable throughput.

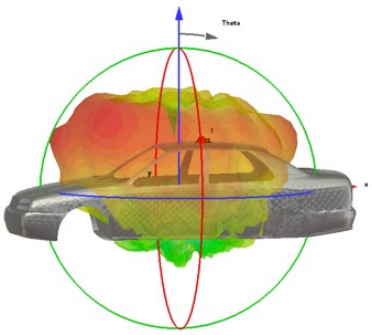
Operating Environments: The effects of placement are more pronounced in weak coverage environments or areas with significant signal obstruction, where installation-related losses more noticeably impact connection stability.

RF Cable Routing: RF cables have defined minimum bend radius requirements; exceeding these can alter impedance characteristics and increase insertion loss. Bundling RF cables with wiring harnesses can also introduce unwanted coupling or electromagnetic interference.

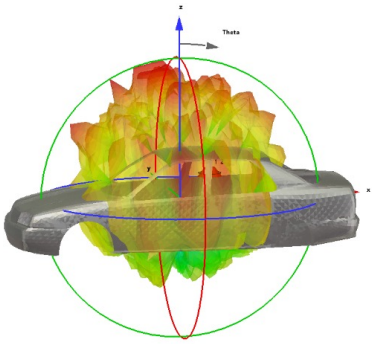
Antenna Placement Considerations:



a) TE Gar multi-port antenna placed on 1x1 m ground plane



b) Radiation pattern of Gar antenna placed on the roof of the vehicle



c) GAR antenna placed inside the vehicle

SMART TRANSPORTATION APPLICATIONS

The following examples represent potential connectivity use cases and do not imply guaranteed performance across all system architectures.

CONSTRUCTION AND AGRICULTURE

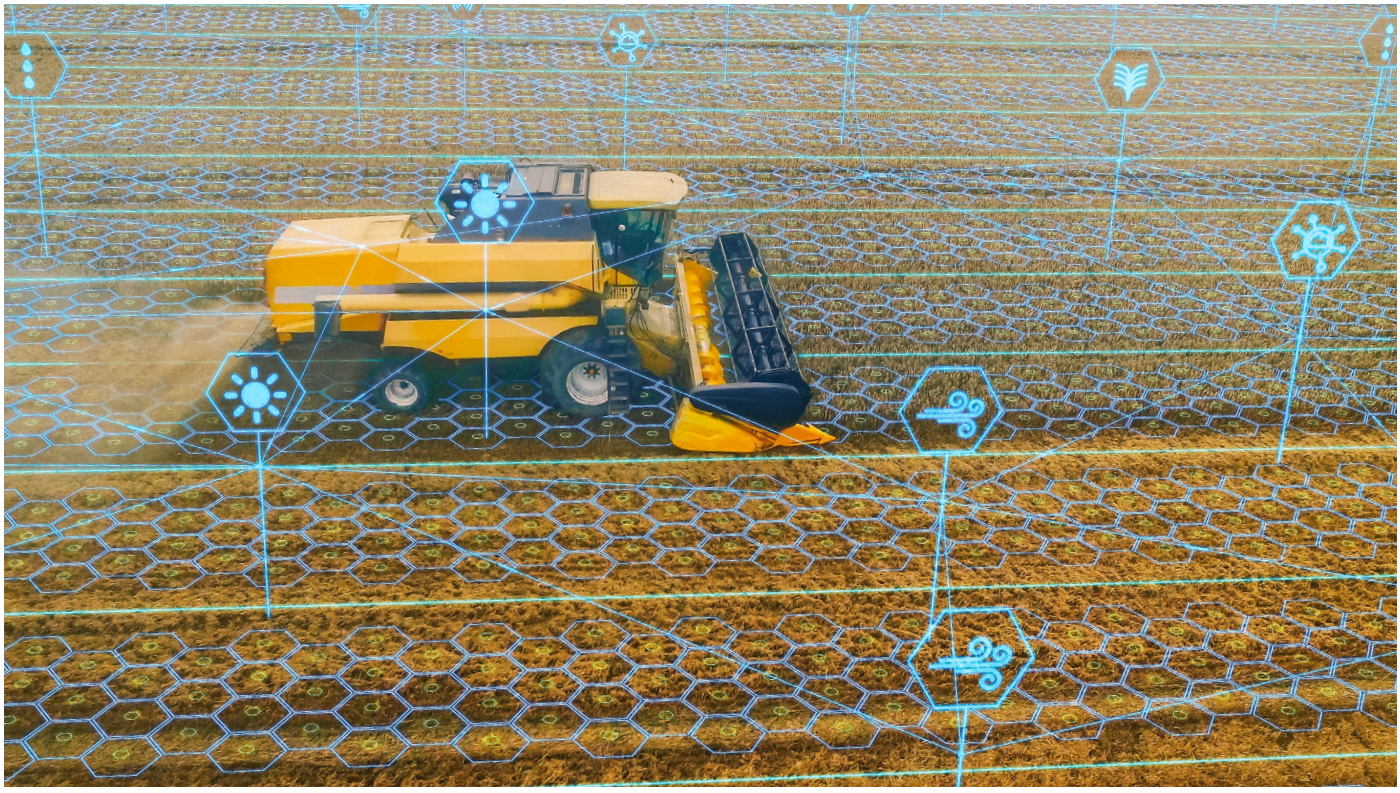
Construction and agricultural equipment increasingly operate in demanding, remote, and mobile environments where connectivity plays a supporting role across daily operations. In construction and agriculture operating environments, connectivity components are commonly used to help support data exchange, sensing, and navigation needs across heavy duty machinery, support vehicles, trailers, and connected peripherals operating in the field.

Within construction and agriculture operating environments, connectivity components are used to support applications such as vehicle and asset monitoring, positioning and guidance, machine diagnostics, and communications between equipment, operators, and backend systems. Global Navigation Satellite System (GNSS) based positioning, combined with cellular, Wi-Fi, and short-range wireless technologies, helps support location awareness and data transmission across both in vehicle and to/from vehicle systems, including trailers and external attachments.

In construction and agricultural operating environments, connectivity components may be deployed in conditions that include vibration, dust, moisture, temperature extremes, and mechanical stress. These components are deployed within increasingly connected machinery ecosystems to support evolving digital workflows, remote visibility, and data driven decision making in construction and agricultural operations.

Construction and Agriculture Antenna Applications:

- Vehicle and Asset Monitoring
- Positioning and Guidance
- Machine Diagnostics
- Communication



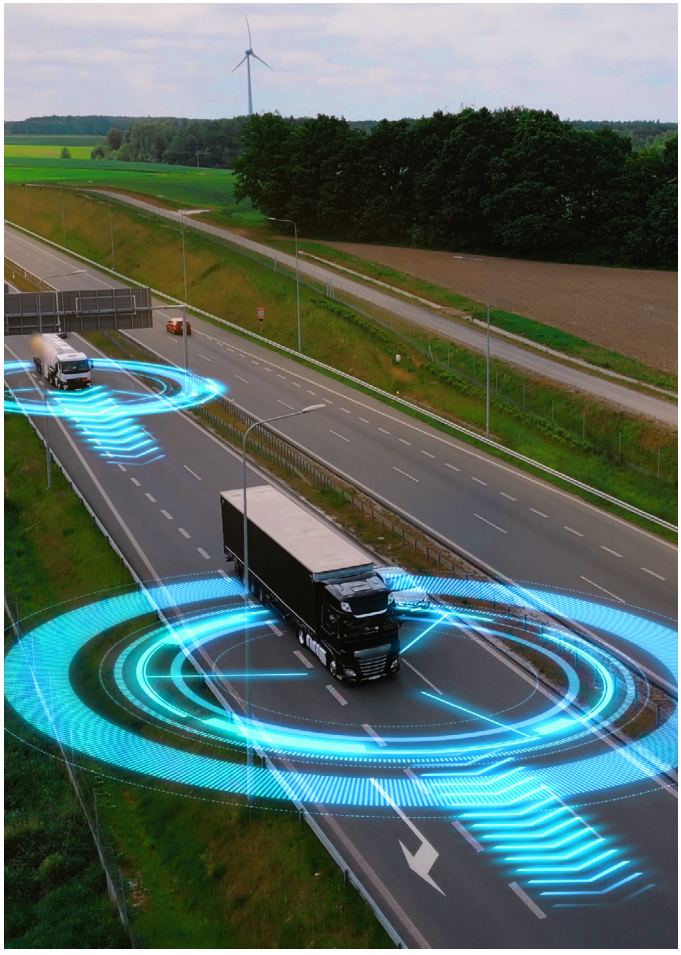
FLEET TELEMATICS

Fleet applications like food and grocery delivery, last-mile logistics, and vehicle tracking rely on antennas to support steady and consistent device connectivity. These vehicles may use multi-band antennas to help provide real-time routing, sync handheld devices, and monitor temperature-sensitive goods. This integrated connectivity supports customers in tracking deliveries in real time and allows drivers to communicate any unforeseen delays.

Fleet transportation systems require high-performing antenna solutions that can withstand vibration and harsh weather elements. They need rugged and compact antennas, integrated across vehicles, from long-haul trucks to electric bicycles. In-vehicle connectivity is also important to ensure the driver's scanners and mobile POS devices remain consistently connected, enabling real-time decision-making and accurate fleet tracking.

Fleet Telematics Antenna Applications:

- Food and Grocery Delivery
- Last-mile Logistics
- Vehicle Tracking



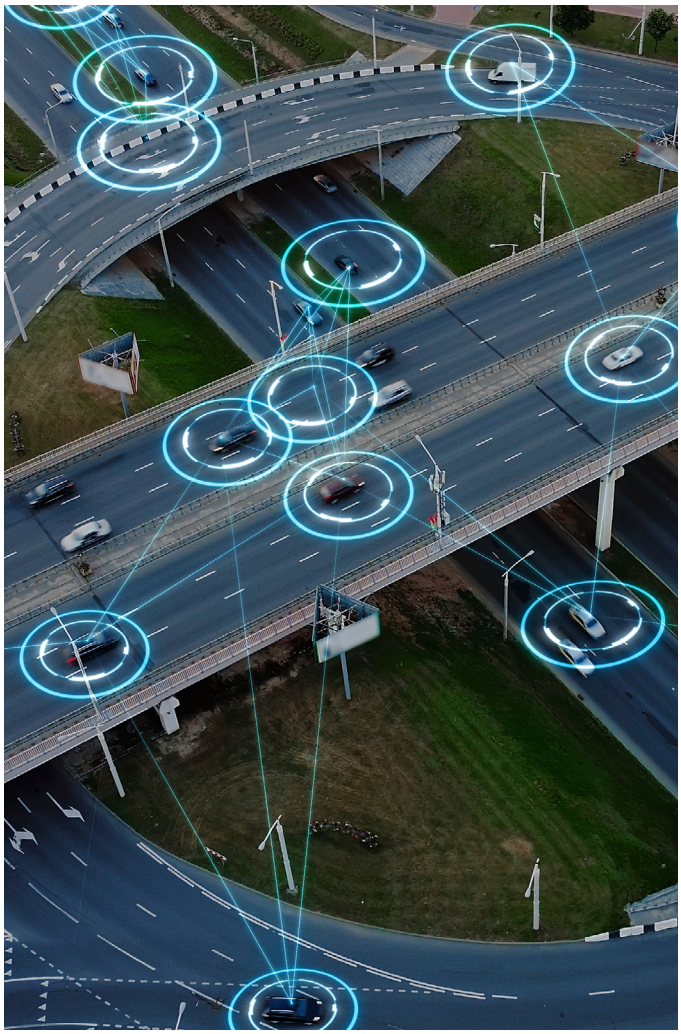
INTELLIGENT TRANSPORTATION SYSTEMS (ITS)

Components designed for Intelligent Roadway Systems help support traffic management, infrastructure monitoring, and roadway system connectivity across public transportation and traffic environments. Through integrated sensing, data processing, and connectivity capabilities, these components help support applications like vehicle and asset tracking, route analysis, scheduling coordination, and infrastructure evaluation within transit and roadway systems.

Within roadway and transit networks, connectivity components can help support data collection, video transmission, and communications between vehicles, control centers, and infrastructure assets. These capabilities can be used in applications such as traffic flow monitoring, system condition sensing, and operational coordination, helping transportation authorities make more informed decisions and manage roadway systems more effectively over time.

ITS Antenna Applications:

- Vehicle and Asset Tracking
- Route Analysis
- Scheduling Coordination
- Infrastructure Evaluation



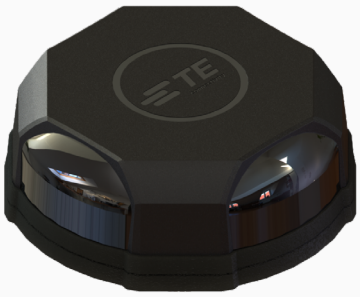
TE CONNECTIVITY ANTENNA SOLUTIONS

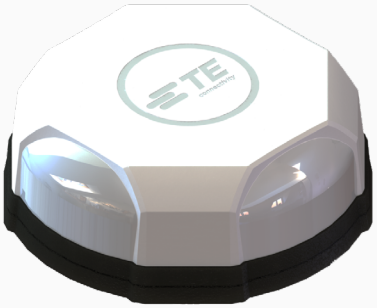
FP40 ULTRA 4X4 MIMO VEHICULAR ANTENNAS

FP40 ultra, vehicle antennas provide an all-in-one solution compatible with LTE/5G, Wi-Fi, GNSS and Bluetooth technologies in high bandwidth mobile connectivity applications.

The product family includes multi-port solutions with up to 14-ports, along with a range of connector options to support integration with many vehicular gateways and routers (compatibility depends on system design and configuration).







Features and Benefits:

- Configurations available up to 14-ports designed to support a range of connectivity requirements
- Compatible with 4G, 5G, CBRS, Wi-Fi, Bluetooth, and GNSS technologies within a single antenna housing
- Designed for applications requiring high data rates and low latency
- Designed to support evolving 4G and 5G frequency deployments up to 7125 MHz
- Connector, cable length and port configuration options available
- Cables options designed to help support R118 compliance needs (confirm requirements for your specific application)
- Manufactured in a TE-owned facility in Malaysia

Key Differentiators:

- Low profile design, 66.5mm height, to help support vehicle clearance requirements
- L1 and L5 GNSS designed to help improve positioning accuracy and response timing
- Out of band rejection filters designed to help support consistent RF performance
- Technologies such as carrier aggregation help to enable high data throughput
- Compatible with a wide range of 4G and 5G frequency bands (617-7125 MHz), including CBRS, Wi-Fi, Bluetooth and GNSS technologies
- Gain patterns designed to support low gain ripple, robust horizon coverage, and antenna efficiency up to 70% under defined conditions (see product documentation for test setup)
- Designed and tested to applicable UV, flammability, humidity, impact, vibration, shock standards (confirm requirements for your specific application)
- IP67 and IP69K rated

FP AUTO MULTI-PORT VEHICLE ANTENNAS

FP20 auto and FP40 auto antennas are designed to help support a combination of 4G, 5G, CBRS, Wi-Fi, Bluetooth, and GNSS compatibility requirements.

The FP20 and FP40 series of vehicle antennas include multi-port configurations (up to 9 ports) and a range of compatible whip antenna and connector options, designed to help support integration with select vehicular gateways and routers, depending on configuration.





Features and Benefits:

- 6, 7, 8 and 9 port options available
- 2x2 and 4x4 MIMO versions
- Wideband coverage
- 4G/5G, Wi-Fi, Bluetooth, GNSS L1+L5 and optional VHF, UHF or 700/800/900 MHz (via high power whip port) compatibility with a single antenna
- Cost-effective option can help to increase bandwidth and signal strength
- Manufactured in a TE-owned facility in Malaysia

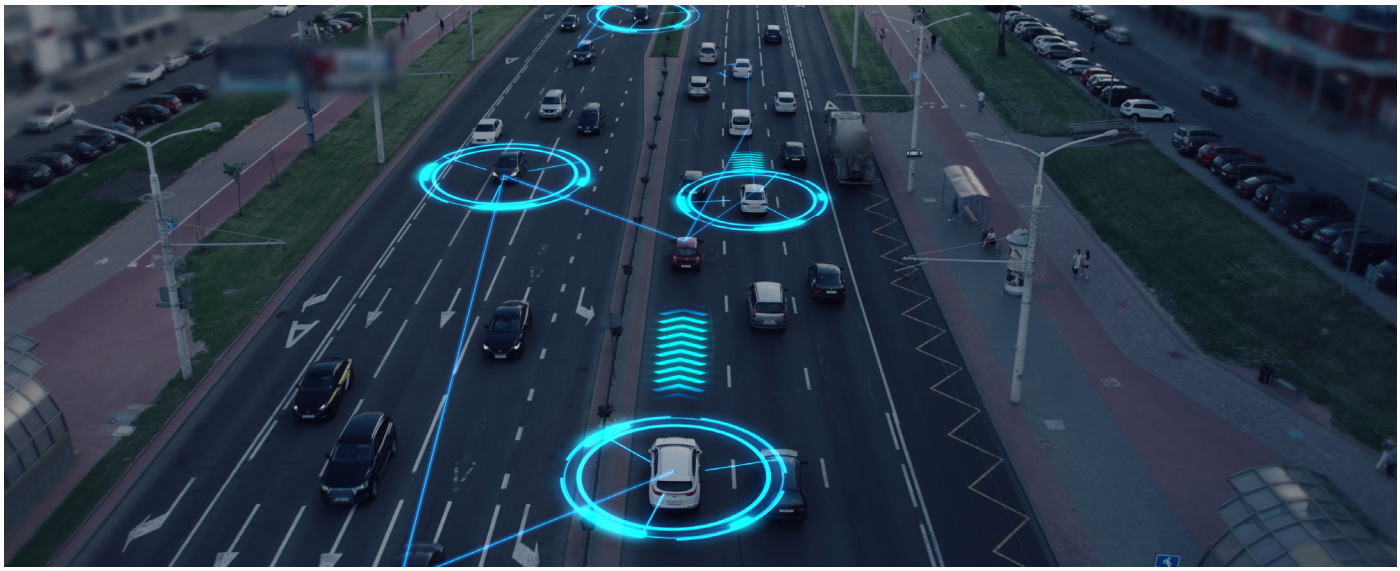
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FUTURE OF ANTENNA TECHNOLOGY IN CONNECTED VEHICLES

The future of antenna technology in connected vehicles continues to evolve through ongoing innovation and emerging developments shaping the industry.

Smaller, more compact antennas that can be integrated into a vehicle's bodywork or hidden from view altogether are becoming more in demand across the transportation industry. The target is reliable, high-speed wireless connectivity without negatively impacting the vehicle's functional design or aesthetics.



Advancement of multi-band antennas capable of operating across multiple frequency bands is critical. This technology is designed to help support transit systems in leveraging a broader range of wireless communications, contributing to connectivity and data transmission capabilities. At the same time, the automotive industry is seeing a growing push toward fully autonomous vehicles, a vision that hinges on secure, reliable, and robust connectivity to ensure safe and efficient operation.

Antenna technology is playing a critical role in transforming transportation and wider connected vehicle applications. From improving the passenger experience to enhancing safety and security, antenna technology is making it possible to enable faster and more consistent wireless connectivity on the move. As new developments and innovations emerge, antenna technology will continue to play a vital role in improving the efficiency and effectiveness of intelligent transportation systems around the world.

As transportation connectivity requirements continue to expand, scalable, high-performance antenna systems remain foundational to the future of smart transportation. TE Connectivity's broad antenna portfolio is designed to help customers address evolving connectivity challenges across fleet, transit, ITS, construction, and agricultural vehicle applications.

ABOUT TE CONNECTIVITY

TE Connectivity is a global industrial technology leader creating a safer, sustainable, productive, and connected future. Our broad range of connectivity and sensor solutions enable the distribution of power, signal and data to advance next-generation transportation, energy networks, automated factories, data centers, medical technology and more. With more than 85,000 employees, including 9,000 engineers, working alongside customers in approximately 130 countries, TE ensures that EVERY CONNECTION COUNTS.
Learn more at www.te.com.

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