QPF5100Q + QPF5501Q

Ultra-Wideband (UWB) Occupancy & Presence Detection Solution

1. Introduction

This application note describes an automotive in-cabin occupancy and presence detection solution based on Qorvo's automotive-qualified QPF5100Q Ultra-Wideband (UWB) System-on-Chip (SoC) used in combination with the QPF5501Q RF front-end (RFFE). It provides system integration guidance with emphasis on RF performance, antenna implementation, and overall system design for reliable in-cabin sensing.

The QPF5100Q operates as the UWB sensing engine, generating nanosecond-scale pulses and capturing channel impulse response (CIR) data to detect occupant presence and analyze reflections within the vehicle cabin. When combined with the QPF5501Q RF front-end, which integrates a power amplifier (PA), dual low-noise amplifiers (LNAs), and an RF switch matrix, the system benefits from improved signal transmission and reception together with flexible antenna routing.

The combined solution enables detection of occupied and unoccupied cabin states without relying on optical or imaging sensors, preserving passenger privacy while supporting scalable in-cabin monitoring architectures. The dual-receiver capability of the QPF5100Q and the antenna flexibility provided by the QPF5501Q support robust signal acquisition in reflective in-cabin environments.

The QPF5100Q is a fully integrated low-power CMOS impulse-radio UWB SoC operating in the 6.5–8 GHz band and compliant with IEEE 802.15.4z. Together with the QPF5501Q, it provides a scalable platform suitable for different vehicle cabin geometries and system configurations.

Qualified to AEC-Q100 automotive standards, the combined solution supports operation across a wide temperature range and enables flexible installation in locations such as headliners, overhead consoles, or vehicle pillars. Its efficient power architecture supports continuous or periodic monitoring, including low-duty-cycle operation during parked conditions.

This document describes recommended system architectures, RF front-end integration, antenna placement strategies, CIR-based occupancy sensing, and system-level considerations to assist designers in achieving robust detection performance and efficient system integration.

2. Functional System Overview

In this architecture, a UWB anchor built around the QPF5100Q and QPF5501Q periodically transmits nanosecond-wide impulse signals into the vehicle cabin through a dedicated transmit (TX) antenna. The QPF5501Q RF front-end enhances the transmitted signal through its integrated power amplifier (PA), improving link budget and enabling consistent signal coverage throughout the cabin. These wideband pulses propagate through the interior environment and reflect from seats, dashboard components, glass surfaces, and any occupants present.

The reflected signals are received by multiple antennas and routed through the QPF5501Q low-noise amplifiers (LNAs) and switch matrix before being captured by the QPF5100Q receive chains (RXA and RXB). This multi-antenna configuration enables reflected signals to be captured from different perspectives within the cabin.

The QPF5100Q captures the channel impulse response (CIR) associated with each transmission, from which delay, range-domain, and multipath information can be extracted. Because UWB signals operate with bandwidths greater than 500 MHz, the system achieves high temporal resolution, enabling discrimination between closely spaced reflectors within the cabin.

When multiple receive antennas are used, CIR measurements from each antenna can be combined to provide additional spatial information. By comparing the relative phase and timing of corresponding CIR components across RXA and RXB, the system can estimate the angle of arrival (AoA) of reflected signals. This enables improved spatial discrimination of reflections and can provide additional information about occupancy distribution within the cabin.

Variations in CIR amplitude, delay, and phase relative to a reference profile are used to identify changes within defined cabin regions. The use of multiple antennas improves detection robustness by reducing sensitivity to fading and blockage.

The QPF5100Q provides embedded processing resources for local control, timestamp handling, and initial feature extraction. Extracted data can then be transmitted to a central Electronic Control Unit (ECU) for higher-level processing such as multi-anchor correlation, sensor fusion, and system-level decision making.

From the vehicle system perspective, the sensing operation is transparent to the user. During parked conditions, the system can operate in a low-duty-cycle monitoring mode to minimize power consumption while maintaining detection capability. If a change in occupancy state is detected after vehicle shutdown, the ECU can initiate further analysis and the appropriate vehicle-level response.

Figure 2-1 shows an example of a single-anchor UWB occupancy detection system within the vehicle cabin.

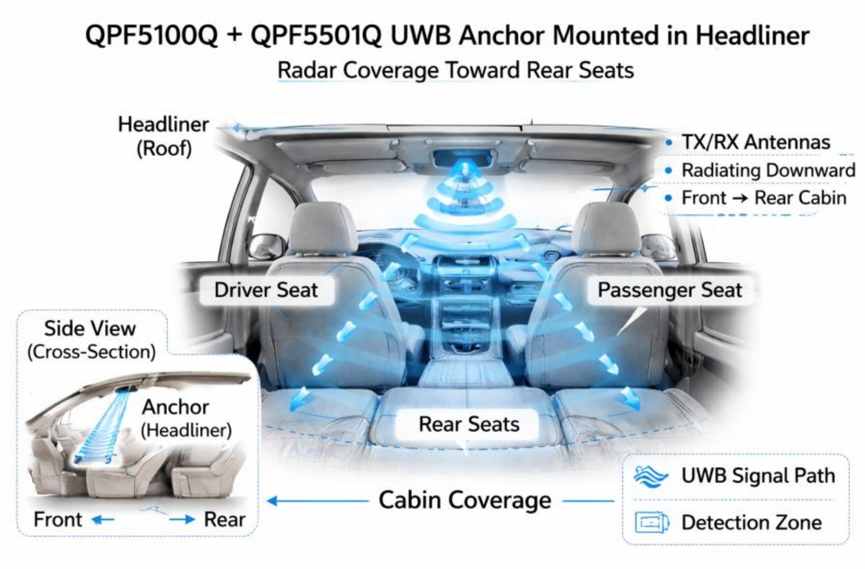

Figure 2-1. Single Anchor UWB Occupancy Detection in Vehicle Cabin

3. High-Level Solution Block Diagram

The block diagram illustrates a typical in-cabin UWB occupancy detection system based on the Qorvo QPF5100Q and QPF5501Q RF front-end. Depending on vehicle size, cabin geometry, and required spatial resolution, one or more distributed UWB anchor modules may be used. These anchors are typically integrated into locations such as the headliner, overhead console, or vehicle pillars to provide effective cabin coverage while minimizing RF shadowing from seats and structural elements.

Each anchor module integrates the QPF5100Q UWB SoC with the QPF5501Q RF front-end, providing the UWB transceiver, embedded processing, RF amplification, and flexible antenna routing required for in-cabin sensing.

The RF architecture includes one transmit (TX) path and multiple receive paths (RXA and RXB) from the QPF5100Q, interfaced through the QPF5501Q to multiple antenna ports. The transmit antenna radiates UWB signals into the cabin, while multiple receive antennas capture reflected signals from the interior environment. This multi-antenna configuration enables improved spatial coverage in the cabin.

The anchor modules interface with a central vehicle Electronic Control Unit (ECU) for system-level data aggregation and processing. Communication between each anchor and the ECU may be implemented over CAN-FD using the QPF5100Q's integrated CAN controller. Figure 3-1 illustrates a representative system implementation, including the QPF5100Q, QPF5501Q, power-management circuitry, and antenna connections.

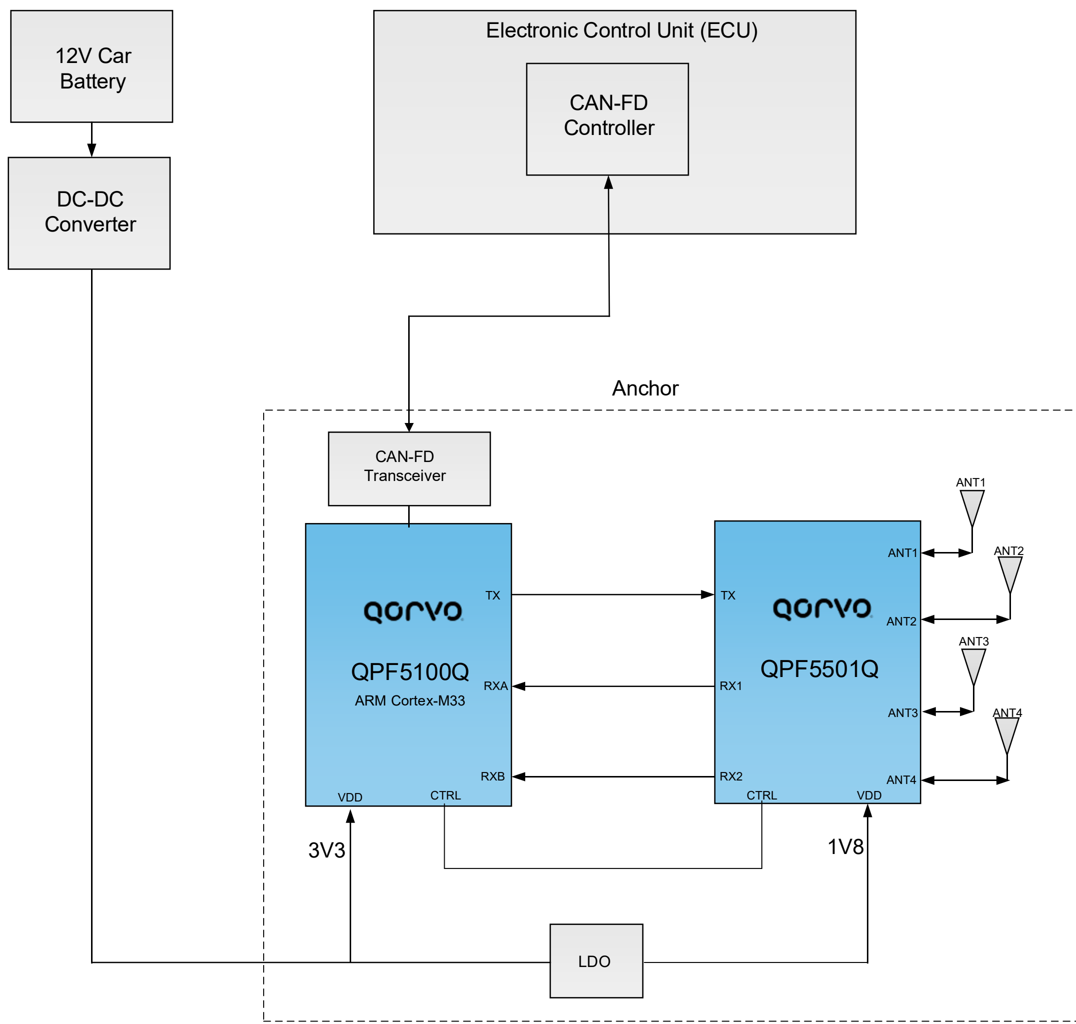

Figure 3-1. UWB Occupancy Detection solution block diagram

The antenna subsystem connects to the QPF5501Q RF front-end, which provides signal conditioning, antenna switching, and routing within the RF signal chain.

Power is derived from the vehicle supply and regulated to provide the required operating voltages for the QPF5100Q and QPF5501Q.

Depending on vehicle geometry and sensing requirements, a single anchor may provide broad cabin coverage, while multi-anchor configurations can improve spatial resolution and robustness through correlation across multiple sensing locations.

Overall, this architecture combines the QPF5100Q's integrated UWB transceiver and processing capabilities with the QPF5501Q RF front-end to enable a scalable and robust in-cabin sensing system suitable for a wide range of vehicle platforms.

4. Antenna Design Considerations

4.1. Antenna Design and Placement

The UWB antennas are a critical element of an in-cabin occupancy detection system because their performance influences sensing coverage, detection reliability, and robustness in the multipath-rich cabin environment. Detecting changes in reflected signal paths caused by occupant presence requires stable antenna performance across the operating band and throughout the intended sensing region.

In an automotive design, the antenna must balance compact size, wide bandwidth, and a radiation pattern that reliably covers the occupant compartment. For the QPF5100Q-based implementation described here, the antenna should support operation across the 6.5 GHz to 8 GHz range and maintain good impedance matching across this bandwidth (for example, VSWR ≤ 2:1 or return loss ≥ 10 dB) to ensure efficient signal transmission and consistent sensing performance.

Sufficient TX–RX isolation is required to minimize transmit signal leakage into the receiver path, which can desensitize or saturate the receiver and degrade sensing performance. This is typically achieved through a combination of antenna placement, physical separation, orientation, and RF front-end isolation.

Linear-polarized antennas are one practical option for in-cabin UWB sensing and can provide well-defined polarization characteristics for system implementation. Circular polarization may also be used in certain configurations; however, reflections within the cabin can alter polarization characteristics and affect received signal levels. Maintaining consistent antenna orientation and radiation characteristics is therefore important.

The radiation pattern should be selected to match the sensing volume of the cabin. A broad, downward-facing radiation pattern is typically used to provide coverage across both front and rear seating areas. Moderate directivity can be beneficial to concentrate energy within the occupant region and improve signal-to-clutter performance. Depending on system requirements, suitable antenna implementations include wideband printed or planar antennas for broad coverage, or patch-style antennas and antenna arrays for more controlled coverage patterns.

Because the antenna is integrated into a complex vehicle environment, nearby structures and materials, including trim components, housings, wiring, and metallic elements, can detune the antenna or distort the radiation pattern. Antenna performance should therefore be verified in the final installation environment using impedance measurements and system-level RF validation. Adjustments to antenna matching or placement may be required to compensate for installation effects.

Figure 4-1 shows an example of simulated radiation coverage for a headliner-mounted antenna configuration, with the antenna oriented toward the occupant region.

Support for antenna selection, integration, and validation is available through Qorvo engineering support channels.

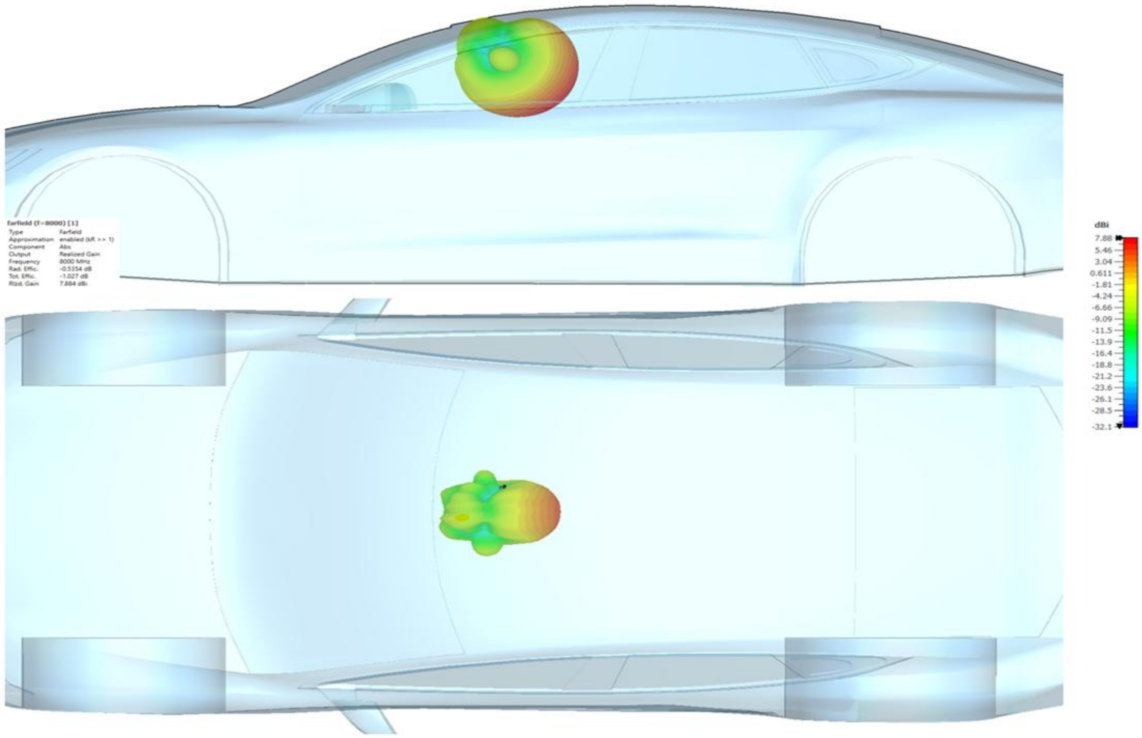

Figure 4-1. Example simulated radiation coverage of a headliner-mounted two-element patch antenna array

5. CIR-Based UWB Sensing Overview

5.1. Occupancy Detection Use Case

Ultra-Wideband (UWB) sensing uses short-duration signals with wide bandwidth (typically around 500 MHz), providing high temporal resolution that enables closely spaced reflections within the vehicle cabin to be distinguished.

The channel impulse response (CIR) represents how transmitted signals propagate and reflect within the cabin environment. The received signal consists of multiple reflection components at different time delays; each associated with one or more propagation and reflection paths within the cabin.

In an unoccupied cabin, the CIR primarily reflects static interior features and remains relatively stable over time. When an occupant is present, additional or modified CIR components may appear at delay values associated with propagation paths involving the occupant, as conceptually illustrated in Figure 5-1.

By comparing CIR measurements over time against a reference profile, the system can identify changes associated with occupant presence and derive information about occupancy state and spatial distribution. Figure 5-2 conceptually illustrates the temporal behavior of CIR measurements under different occupancy conditions.

This CIR-based approach provides a non-imaging sensing method that preserves passenger privacy while supporting robust occupancy detection.

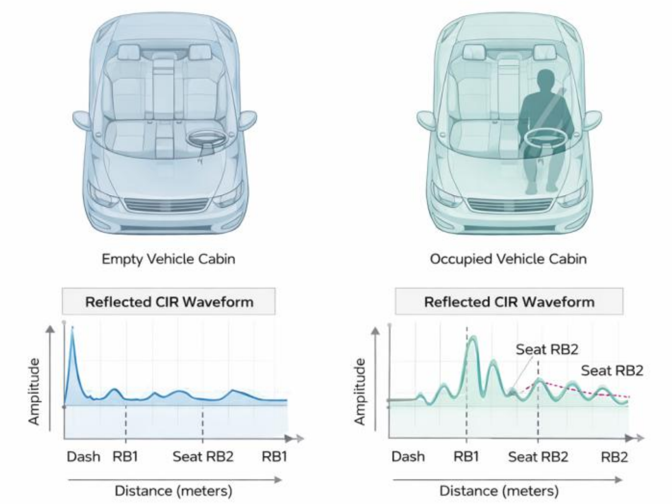

Figure 5-1: Conceptual illustration of CIR in an unoccupied cabin (left) and an occupied cabin (right), showing additional or modified reflection components associated with occupant presence.

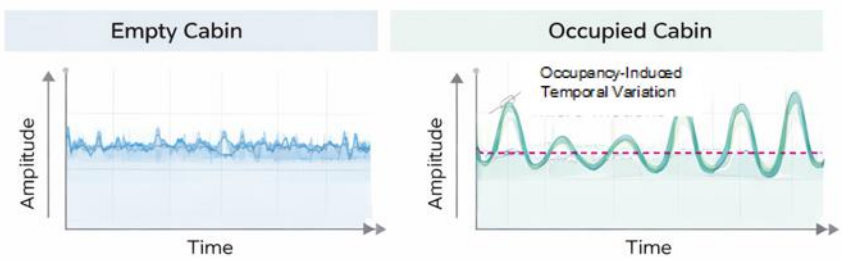

Figure 5-2: Conceptual illustration of CIR measurements over time for unoccupied and occupied cabin conditions, highlighting changes in reflected signal components used to determine occupancy state.

6. Summary

Ultra-Wideband (UWB) channel impulse response (CIR) sensing provides a privacy-preserving approach for in-cabin occupancy detection. The QPF5100Q supports detection of occupant presence and estimation of spatial occupancy distribution within the vehicle cabin.

Combined with the QPF5501Q RF front-end, the QPF5100Q provides a scalable CIR-based sensing platform with improved link budget, receiver sensitivity, and flexible antenna configurations suitable for a range of vehicle cabin geometries and system architectures.

Appropriate RF front-end integration, antenna placement, and system-level implementation are important to achieving reliable occupancy detection across different vehicle cabin configurations.

Revision History

Revision	Author	Date	Description
A	Stuart Williams	14 Aug 2026	Initial draft

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