

## Case Study – Lightbar Antennas in Emergency Vehicles for Preemptive Services

By Chris Talbert, Mobile Mark and Scott Morell, Danlaw

### The Companies:

- Danlaw – V2X Equipment Manufacturer, System Integrator for project
- Code-3 – Rooftop Lightbar Manufacturer
- Mobile Mark – Antenna Manufacturer



*Figure 1: Test vehicle assembled by project partners.*

### The Background:

To help emergency responders to travel safely and know what is around corners, Danlaw developed the Traffic Signal Preemption Application for emergency vehicles.

The system includes a lighting bar with a C-V2X antenna and on-board unit (OBU) that interfaces with the electronics that run the warning lights and sirens. When the driver turns on the siren and the vehicle is approaching the intersection, the program is initiated, to notify via C-V2X the roadside units (RSU) that are connected to the traffic light controllers.

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### *The Background Continued...*

"The vehicle requests that the signal stay green and moves through it without worrying about cross traffic. It can also inform the driver of other hazards. The system offers in-vehicle notifications, shows the timing of the traffic signals and other emergency vehicles," says Andrew Donaldson, Program Manager Connected Vehicles, Danlaw.

The system is being tested in Sterling Heights, Michigan where a fire chief was able to save a patient's life using the technology.

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### **The Challenge:**

- Design antenna to operate in a high-speed environment; cover longer range because of the speed
- Continue to operate in a high temperature environment
- Provide additional signal links to accommodate the large volume of data transmission
- Provide flexibility to move to Dual-Carrier MIMO in the future

A reliable wireless connection was needed for Emergency Vehicles that would be part of a Preemptive Service System. The vehicles, primarily police vehicles, would need to communicate over longer distances due to the high speeds at which they are traveling. The initial trials found that the original antennas did not provide sufficient coverage over the range required and Danlaw was looking for better alternatives.

As the project unfolded, additional challenges were raised. The antenna was to be installed within the roof-mounted lightbar and needed to fit within its physical dimensions. It would also be subjected to periodic spikes in temperature and needed to perform in those conditions.

Danlaw expressed that they would probably need MIMO for 5.9 GHz and LTE as well as L1, L2 and L5 GPS functionality. The Lightbar Manufacturer expressed an interest in adding additional communication links in the future, so the current design needed to consider those possible upgrades. The initial project was design for Public Safety Vehicles, but the application can be expanded to other DOT vehicles, i.e., road plows, tow trucks. Each setting will have its own challenges, but the approach to design and proof-of-concept (POC) will be similar.

This system used the 5.9 GHz band for immediate communication within a V2V (vehicle-to-vehicle) safety system for emergency vehicle preemptive service, crash avoidance and the sharing of other vital safety information. However, additional telematic information from the onboard unit was being collected and needed to be shared. The 5.9 GHz elements, with limited bandwidth at 5.9 GHz, could not handle all of the data that needed to be transmitted. Very critical real-time data would be sent over 5.9 GHz with the rest of the data sent over LTE.

Future plans could call for Dual Carrier or 4x4 MIMO LTE, 4x4 MIMO for the 5.9 GHz band, as well as an L1, L2, L5 GPS antenna, all in the same package.

Limited mounting space raised the possibility that the system might experience interference among the antenna elements, and that the coverage range might be reduced.



## The Solution:

- Evaluate the mounting limitations and develop optimal coverage within those parameters
- Optimize antenna elements for peak performance and range
- Ensure antenna performance in extreme conditions such as high temperatures

The Mobile Mark Antenna Engineers modeled different scenarios and developed prototypes to test out various configurations. Characteristics of these antennas will be explained below.

Once the prototype antenna design was finalized, it needed to be tested in the field. The System Integrator developed a controlled test bed to compile the real-world communication measurements with the Onboard equipment.

The final configuration resulted in a drastic improvement in the range covered. The range increased from 200 meters to 600 meters. This extended range was crucial for police vehicles traveling at high speeds.

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## The Antenna:

- Develop antenna systems with 2x5.9 GHz, 2xLTE & 1xGNSS
- Position elements to minimize interference among elements and maximize coverage range
- Test antenna elements (Cellular & GNSS) for performance at high temperatures

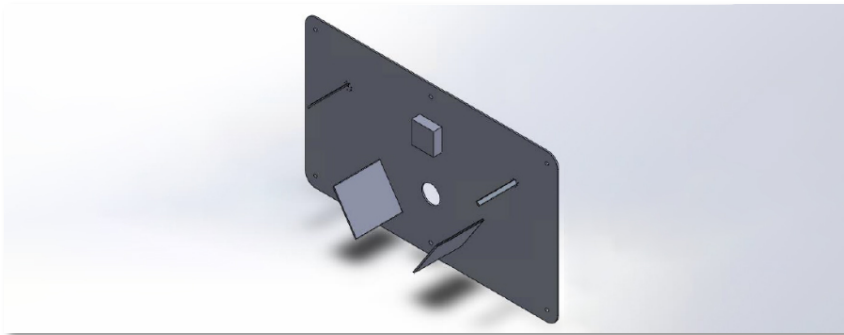
## The Antenna Continued...

The Antenna Prototype developed contained five elements: 2x5.9 GHz, 2xLTE & 1xGNSS:

Two DSRC/C-V2X passive antennas (2 x 5.9 GHz): These antennas were omni-directional antennas covering the desired 5.850-5.925 GHz range with a peak gain at 6 dBi. The radiation pattern measurements showed strong performance with highly favorable patterns on front/back and left/right. The 2-element MIMO (multiple-input-multiple-output) design allows for greater data throughput.

One GPS/GNSS active antenna (1560-1602 MHz): The antenna had Right-Hand Circular Polarization (RHCP) with a peak gain of 33.5 dBic gain. The antenna showed excellent performance measurements.

Two LTE passive antennas (2 x 4G Global LTE): These antennas were omni-directional antennas covering 694-960 MHz (peak gain of 2 dBi) & 1710-3700 MHz (peak gain of 6 dBi). The radiation patterns were favorable with strong coverage in all directions. As with the 5.9 GHz elements, the 2-element MIMO design accommodates larger volumes of data with more reliability.



The five antenna elements were soldered onto an FR4 PCB material measuring 12" L x 7" W (30.5cm x 17.8cm)

Antenna design modeling and prototype testing determined the best position for the five elements.

**Figure 2.** Drawing of Dual-Mode Antenna with 5-elements: 2x5.9 GHz, 1xGNSS, and 2xLTE.

The antenna installation setting was predetermined to be in the roof-mounted light bar, which had size and material constraints. There needed to be sufficient groundplane for the optimal performance of the antennas, and the antennas need to be spaced to prevent signal interference among the antenna elements, and to provide maximum coverage range.

Antennas need sufficient groundplane to provide peak performance. In this case, the antenna was designed with the groundplane incorporated so the overall 5-element package and therefore the antenna was groundplane independent.

The physical housing of the lightbar system posed some challenges. During the initial testing, the antenna radiation pattern was being bent and therefore reducing the antenna's radiation pattern performance. Multiple rounds of empirical testing were conducted to optimize the antenna being integrated into the lightbar in order to maintain peak performance.

In addition, adjustments to the lightbar system itself were recommended to improve the overall coverage range.

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## Mechanical Testing:

- Temperature specs
- Vibration specs

The two most critical mechanical tests conducted were: Temperature Cycling and Shock & Vibration.

The antenna package needed to be designed to meet short bursts of ambient temperature spikes of 105°C. This is important because temperatures can reach excessive levels within a sealed lightbar, especially on a hot summer day, with the lightbar fully lit-up.

The most sensitive component was the GNSS element. To confirm its ability to meet the specs, the antenna was subjected to empirical temperature testing in a simulated installation setting. The antenna was tested with hot & cold cycling in a Temperature Chamber to meet MIL-STD-810F spec. To complement the antennas, the entire unit was upgraded to high-temperature cables.

The antenna elements were provided on the PCB board without any housing. The Lightbar would provide most of the mechanical protection for the antenna, but additional steps were taken to ensure the antenna was robustly constructed.

The antenna was tested in a Vibration Chamber to model the conditions that might be experienced by the Emergency vehicle. Shock & Vibration measurements were taken to ensure that the antenna would meet Military & Industrial standards: EN 61373:1999, IEEE 1478-2001, and Mil-STD-810G.

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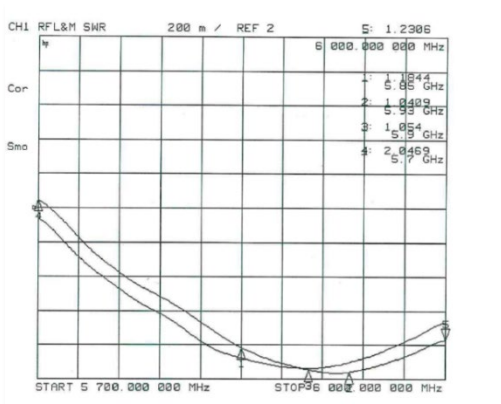
## Electrical Testing:

- VSWR plots
- Radiation patterns

Initial testing consisted of running VSWR tests to measure the signal match. This test is an indication of the amount of mismatch between an antenna and the radial (cable) connecting to it. In effect, it measures the efficiency of the design and whether power and signal loss exist in the design. The test was conducted on a 12-inch groundplane with 1-foot of cable for each element. The antenna is connected to a network analyzer that generates the VSWR plot.

Electrical Testing Continued...

EDN341-1100 – 2x 5.9 GHz VSWR PLOTS

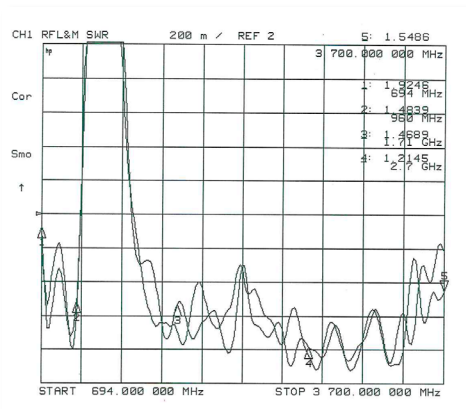


**Figure 3.** VSWR plot for 5.9 GHz antenna elements.

The target measurements for VSWR are typically spec'd less than 2:1.

Measurements for the 5.9 GHz elements range from 1.18:1 at 5.85 GHz to 1.05:1 at 5.9 GHz. These are excellent readings and demonstrate the responsiveness of the antenna.

EDN341-1100 – 2x LTE ( 694 – 960 / 1710 – 3700 MHz ) VSWR PLOTS



**Figure 4.** VSWR plot for LTE antenna elements.

Measurements for the LTE elements ranged from 1.9:1 at 694 MHz to 1.2:1 at 2700 MHz.

The LTE elements are specified for 694-960 MHz and 1710-3700 MHz.

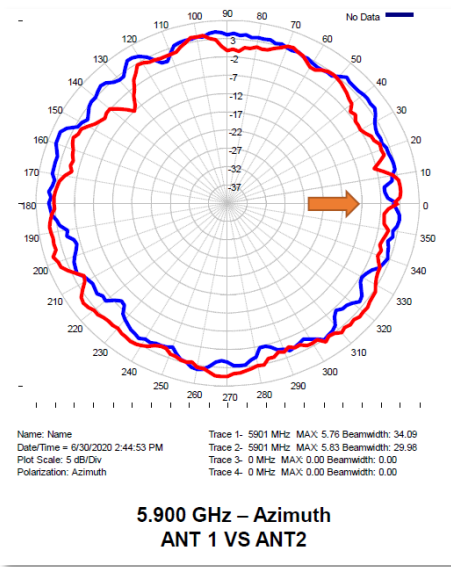
There are no Cellular signals in the 960-1710 MHz band, therefore VSWR measurements in this space are not part of the antenna design.

*Electrical Testing Continued...*

To evaluate the radiating pattern of the antennas, the prototype 5-element antenna was set up in the Anechoic Chamber to simulate its position on the vehicle.

Three sets of patterns were run: Azimuth (horizontal), Elevation (vertical), and Left & Right-Side Elevation patterns at different points in the DSRC/C-V2X band. The most important pattern for this project is the Azimuth pattern because the vehicle should be able to communicate reliably in all 360° directions.

The simulation also accounted for the fact the antenna was to be mounted inside the lightbar.



The measurements were taken at 5.9 GHz, which falls in the middle of the 5.85-5.925 GHz band.

It is also positioned above the 5.85-5.895 GHz portion of the band which in the process of being repurposed by the FCC for unlicensed commercial uses such as WiFi.

The Emergency Over-ride system was designed for diversity coverage on the LTE channel, allowing the system to select whichever signal is stronger.

The two patterns shown here (red & blue) correspond to the two antennas that work together for MIMO coverage (multiple-input-multiple-output).

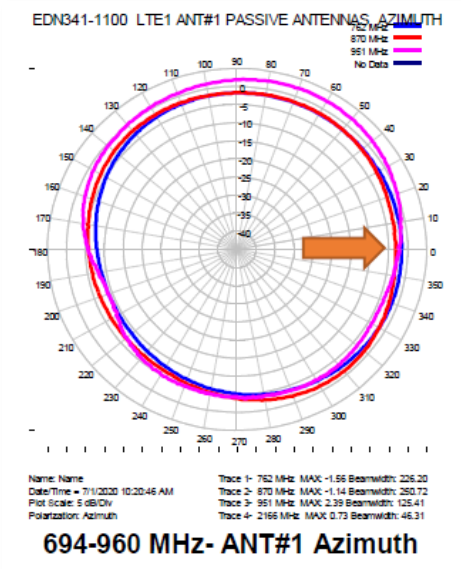
Both 5.9 GHz antennas show reasonably rounded pattern without deep nulls in any direction, thus assuring continuous and reliable coverage.

**Figure 5.** Azimuth (horizontal) radiation pattern showing balanced coverage in all 360-degree directions

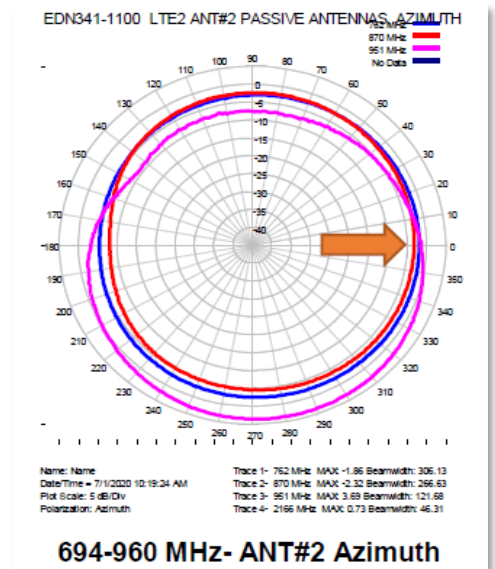
The LTE elements cover a considerably wider frequency band than the 5.9 GHz. To fully capture the performance of these LTE elements, the VSWR plots were taken at different points from 694 – 3700 MHz. For the sake of space, we are presenting just the 694-960 MHz band as illustration.

Different Cellular Carriers will rely more heavily on one part of the LTE band than the others. Since this project is designed in large part for Police and other Public Safety vehicles, it was particularly relevant to have strong coverage for the FirstNet system in the 700 MHz band.

Electrical Testing Continued...



**Figure 6:** Azimuth (horizontal) pattern for the first LTE element. The orange arrow indicates the front of the vehicle



**Figure 7:** Azimuth (horizontal) element for the second LTE element. The orange arrow indicates the front of the vehicle

The radiation patterns for the two LTE elements are presented in separate images here to capture different points in the 694-960 MHz band in each radiation pattern shown. While there are slight differences from one band to the other, all show very well-balanced coverage. Working together for MIMO coverage, these elements provide reliable coverage.



**Field Testing:**

Field Testing of the Prototype Lightbar Antenna was carried out by the System Integrator in Livonia, Michigan.

A 900-meter (0.56 mile) section of a straight road was cordoned off for a high-speed trial allowing the system integrator to simulate a real-life experience. A host vehicle and remote vehicle were used to measure the signal strength, distance, and consistency.



Figure 8. Host vehicle with roof-mounted Lightbar.

Two test vehicles were used:

- Host vehicle with light bar antenna
- Remote vehicle with reference antenna

Onboard unit (OBU): Both test vehicles used Danlaw C-V2X/ OBU which were transmitting and receiving message with a configuration of 10 MHz and packet size of 360 Bytes. Both of the OBUs were using channel 184. The software was the same as previously used in the range test as well as in congestion test.

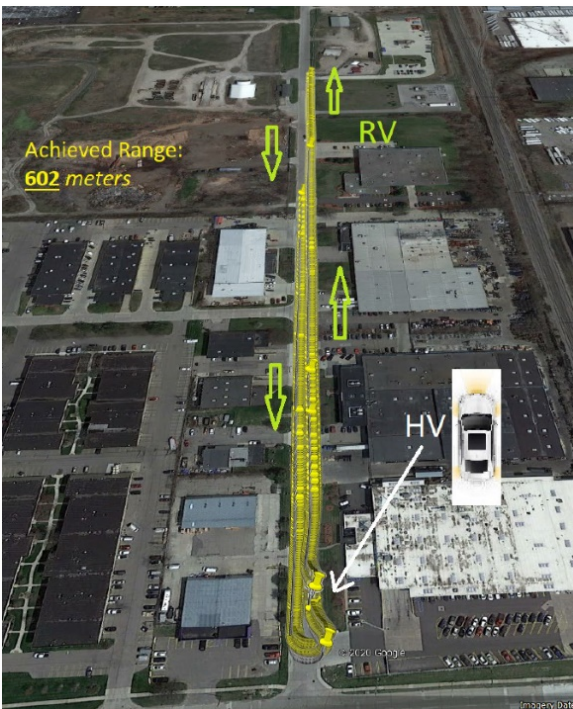


Figure 9. First run conducted on test bed.



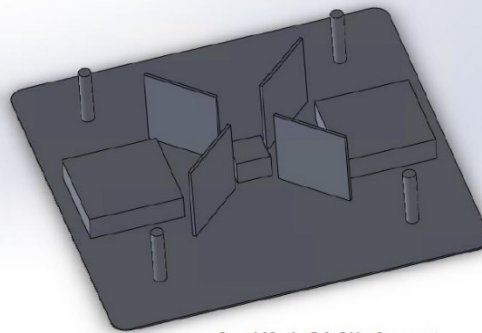
Figure 10. Second run conducted on test bed.

## Future Design Concepts:

The next generation antennas will accommodate one of the following designs:

- Dual-mode: 2x5.9 GHz, 1xGNSS, and 2xLTE
- Quad-mode: 4x5.9 GHz, 1xGNSS (L1, L2), 2xGPS (L1, L2, L5), and 4xLTE; with 4-8 WiFi passive antennas as add-on option.

**Figure 11.** Future design with 11 antenna elements.



Quad Mode 5.9 GHz Concept

Drawings of these concepts are completed but cannot be shared at this time due to NDA constraints.

Please contact one of the companies involved in this project for further information.



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