B2V 2020: The Year in Technical Progress

Prototype Development, Shared Software and Bluetooth® Wireless Technology Testing

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Tome

Abstract

The global pandemic changed almost everything in 2020, but it didn't stop technical innovation for bicycle safety for the B2V Working Group. Our work for the calendar year included launching and updating a shared codebase within the Group, the development of prototypes (HDK and OEM) and Bluetooth® Low Energy performance testing of the prototypes. The OEM and HDK prototypes send a personal safety message (PSM) from vulnerable road users' devices to a vehicle using Bluetooth LE wireless technology version 5.x. The HDK work was a continuation of technology demonstrated at the 2019 workshop that introduced a prototype device using Bluetooth LE 5.x wireless technology with extended advertisements and Coded PHY. This paper also identifies known issues, next steps and reference links.

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Glossary

Angular and G-Force Indicator (ANGi): ANGi is a small Bluetooth hardware sensor developed by Specialized Bicycles which is mounted to a rider's helmet and detects impact events which could impair consciousness.

Advanced Driver Assistance System (ADAS): Electronic systems that aid a driver, intended to increase vehicle safety and, more generally, road safety.

Basic Safety Message (BSM): A BSM is used in a variety of applications to exchange safety data regarding vehicle state. (Reference SAE J2735)

Bicycle-to-Vehicle (B2V): Wireless communication from a bicycle to a vehicle containing information about its presence.

Bluetooth® Wireless Technology: A now-ubiquitous, short-range radio technology to support connectivity and collaboration between different products and industries.The Bluetooth word mark and logos are registered trademarks owned by Bluetooth SIG, Inc.

Coded PHY: Changes to the Bluetooth wireless technology specification at the physical ("PHY") layer to extend signal range.

Extended Advertisements: Changes to the Bluetooth wireless technology specification that provide up to 255 bytes within advertisement packets.

Flare® RT: Bontrager® rear bike light ("R" for rechargeable,"T" for tail light), which is compatible with the Bontrager Transmitr remote or the wireless ANT+ light profiles.

Global Navigation Satellite System (GNSS): A constellation of satellites providing signals from space that transmit positioning and timing data to receivers to determine a precise location. The United States' GPS is one such GNSS.

Hardware Development Kit (HDK): B2V prototype device for use in sending/receiving BSM and PSM data packets for data logging, sensor and scenario testing and simulation of sender/receiver vehicle.

Inertial Measurement Unit (IMU): A device that measures the specific force, angular rate and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes and magnetometers. The data collected from the IMU's sensors allows a computer to track a vehicle's position, using a method known as deduced ("dead") reckoning.

Personal Safety Message (PSM)**:** A PSM is used to broadcast safety data regarding the kinematic state of various types of vulnerable road users (VRUs), such as pedestrians, cyclists or road workers. (Reference SAE J2945/9)

microSD™ card (SD card): A type of very small memory card typically used in mobile phones, embedded systems, cameras and other portable devices.

Roadside Unit (RSU): A device that provides connectivity support to passing vehicles.

System on a Chip (SoC): An integrated circuit that bridges all or most components of a computer or other electronic system. (Reference Wikipedia)

Telematics Control Unit (TCU): The embedded system onboard a powered vehicle that controls tracking of the vehicle.

Vulnerable Road User (VRU): Non-automobile/truck road users, such as pedestrians, road workers and cyclists, as well as animal-drawn vehicles and persons with disabilities or reduced mobility and orientation.

B2V Background

In 2017, Tome engineers began working on projects within a larger company program related to bicycle-to-vehicle (B2V) safety. We engaged with multiple entities in the cycling, automotive, governmental and smart city sectors to identify solutions for creating communication systems between vulnerable road users (VRUs) and vehicles.

The B2V Advisory Board consists of representatives from Alta Cycling Group, Bosch, Dorel Sports, Ford, Garmin, Giant Bicycles, GM, Lear, Nordic Semiconductor, Orbea, Panasonic, QBP, Shimano, Specialized, SRAM, Stages Cycling, Subaru, Tome, Trek and Uber.

The B2V mission is simple: Make roads safer for cyclists.

In 2019, we worked alongside Ford and the Crash Avoidance Metrics Partnership (CAMP) to create a demonstration that showed key use cases and a solution where B2V communication could provide automotive value. An e-scooter was also included in this demonstration.

The B2V Working Group began its related software/hardware research and development in 2020. Research and development is focusing on technical solutions to transmit cyclist information to vehicles, using new and existing products as prototypes. Transmission of this data is currently using Bluetooth LE wireless technology. This group consists of technical representatives from Ford, GM, Lear, Nordic, See.Sense, Shimano, Specialized, SRAM and Trek.

In 2020, the Tome B2V prototype continued advancing its features for use within R&D environments. The **Trek Bicycle Corporation** produced a B2V prototype enhancement of their existing Flare® RT bike light, and **Specialized Bicycle Components, Inc** developed a B2V prototype using their existing Specialized Ride app. A shared codebase was developed and integrated into these prototypes.

For more information, or if your group is interested in contributing to open B2V standards, please contact our B2V team at b2v@tomesoftware.com.

To access the white paper from the 2019 Bicycle-to-Vehicle (B2V) Workshop, please visit https://www.tomesoftware.com/wp-content/uploads/2019/10/B2V-Whitepaper-VRU-BSMs-over-BT5-October-28-2019.pdf.

Why Bluetooth® Wireless Technology for Initial Prototypes?

Bluetooth wireless technology has been widely used as a consumer point-to-point and one-to-many radio protocol for many years. After considering other bicycle-to-vehicle communication methods available at the time, Bluetooth wireless technology was the logical starting point to begin B2V communication development.

Bluetooth wireless technology offers immediate advantages:

- Bluetooth radio protocol is well-established. It is ubiquitous in products, from computer mice to in-vehicle infotainment and the Internet of Things.
- Bluetooth standards are well-documented and freely available from the Bluetooth® Special Interest Group (SIG). “Adopter” level membership in the SIG is free.
- Bluetooth hardware and protocol stacks are available from a number of chip manufacturers.
- Bluetooth development boards are not expensive and their workings are typically well-documented.
- Bluetooth wireless technology works in the unlicensed industrial-scientific-medical (ISM) band.
- The Bluetooth Low Energy (LE) mode conserves precious battery power.
- Bluetooth LE v5.x wireless technology enables transmitting devices to advertise their existence and provide up to 255 bytes of data in each advertisement. This broadcast doesn’t require pairing between devices. It is a casual communication of a safety message.

It should be noted that our implementation of B2V tools using Bluetooth LE technology doesn’t preclude Tome from investigating and developing other rising communication technologies (such as C-V2X), as appropriate. Our goal is to convey a robust, secure safety message from a vulnerable road user to a vehicle using whichever technology makes sense.

Prototypes

Overview - Introduction to 'Sender' Devices

In contemplating different B2V communications -- we researched ground sensors, cameras, LIDAR and other techniques -- we decided that the bicycle or e-scooter (the vulnerable road user or "VRU") should broadcast their position and velocity directly to vehicles. Once the vehicle received the VRU position and velocity, that data was more easily processed by the in-vehicle telematics without reliance on roadside relays.

The transmission path is one-way from the VRU to the vehicle. This scheme has the benefit of using simpler, lower-cost hardware for the VRU. Another advantage is longer battery life for the VRU-mounted device, which can be mounted in a helmet, on a smartphone, or within a bike headlight. Additionally, the VRU doesn't need a display or haptic feedback. Perhaps best of all, the scheme is an evolutionary path for commercially-available aftermarket products.

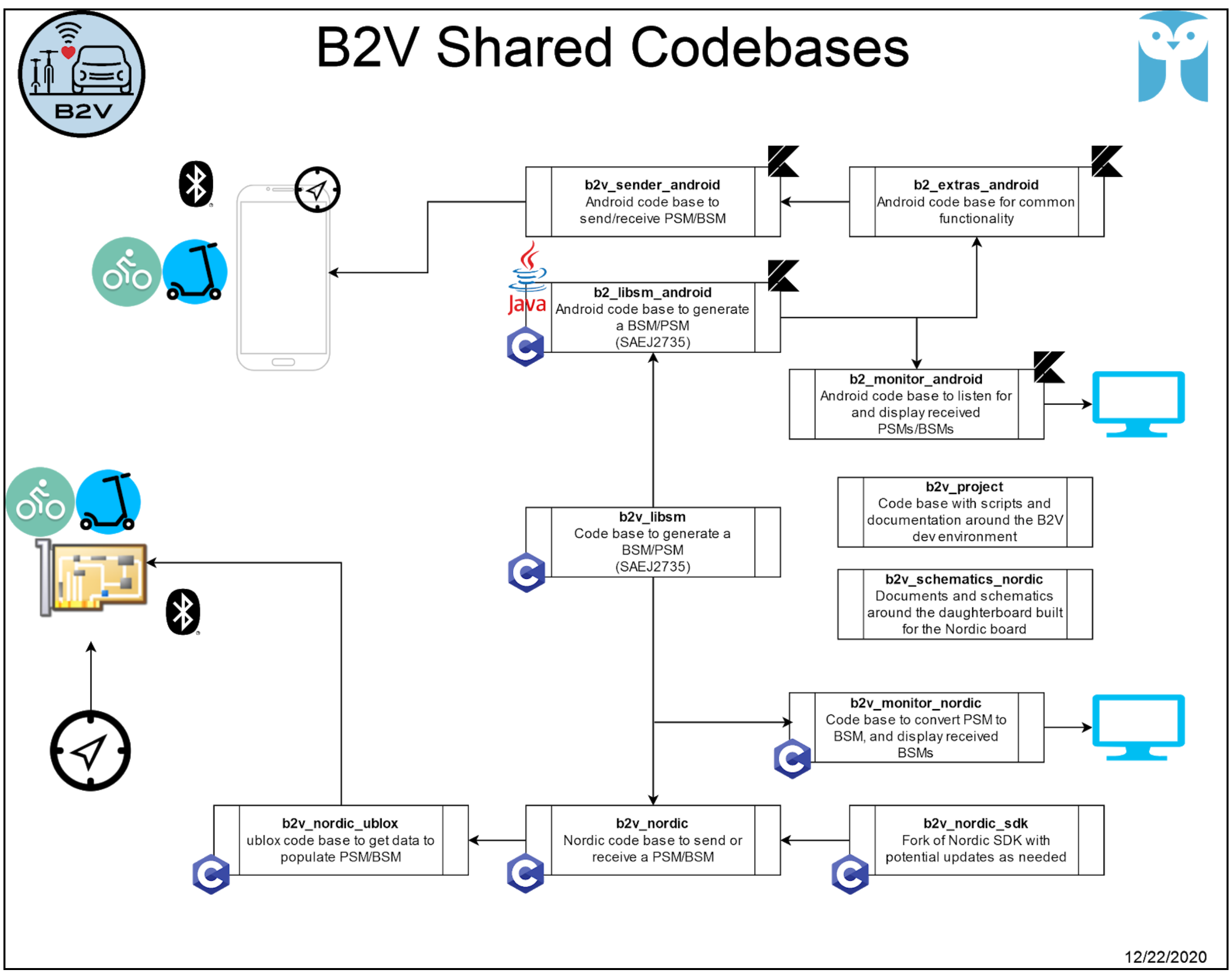
In this section, we will share the details of the underlying software development and the Hardware Development Kit for getting started with B2V. We'll also look at several commercial products that have evolved to include B2V features.

Shared Codebase

The B2V Working Group has developed a shared codebase this year for functions related to the sending and receiving of safety messages. The main intent of this codebase is to be an open and shared source containing the base functionality of creating, populating, sending and receiving of both a PSM and BSM. This also includes the functionality to encode and decode the safety message. Any user experience or functionality on top of this would be proprietary to the integrator of the code, and would not be necessary to share back into the codebase.

Currently, the shared codebase is implemented for Android and Nordic devices that support Bluetooth 5. Specifically, that hardware must support Coded PHY and extended advertisements since these features provide the additional range and increased message size required for transmitting the safety messages. Of note is the b2v_monitor_nordic codebase that can be compiled and run on Windows, Mac and Linux computers/laptops.

Figure 1. The B2V Shared Codebases and Dependencies



Hardware Development Kit (HDK)

Why an HDK?

At the heart of the current B2V hardware is Nordic Semiconductor's nRF52840 system on a chip (SoC), selected for its adherence to Bluetooth 5 and Bluetooth Low Energy (LE) standards, ample flash and RAM (1MB/256kB respectively), extensive SDK and documentation, a well-supported Bluetooth software stack and useful libraries for interfacing with the outside world.

Nordic's nRF52940-Development Kit (DK) combines the SoC with a integral debugger; programmable, on-board LEDs and buttons; Bluetooth antenna jack; and headers exposing GPIO, SPI, I2C, serial, USB, and other signals which made initial Bluetooth development quite straightforward. The DK is also economical, with a retail price under $50USD.

Nonetheless, as the B2V software grew in sophistication, it became apparent that we needed to design an accessory board to plug into the DK's headers to: connect devices to log data; provide a way to easily configure the DK to be a sender or a receiver (or both); to provide convenient connectors to external devices; and other forward-thinking features.

Our accessory board was named Hardware Development Kit.

What Components are on the HDK?

The photo below shows the evolution of the HDK, from the early hard-wired perfboard to a surface mount component version.Three features have remained on the HDK throughout and are discussed further below:

1) A microSD card slot for data logging to aid in gathering insight to naturalistic behavior.
2) A DIP switch containing four or more individual switches.
3) A seven-pin connector to interface with a GPS/inertial measurement unit (IMU) device.

Figure 2. The HDK Prototype evolution

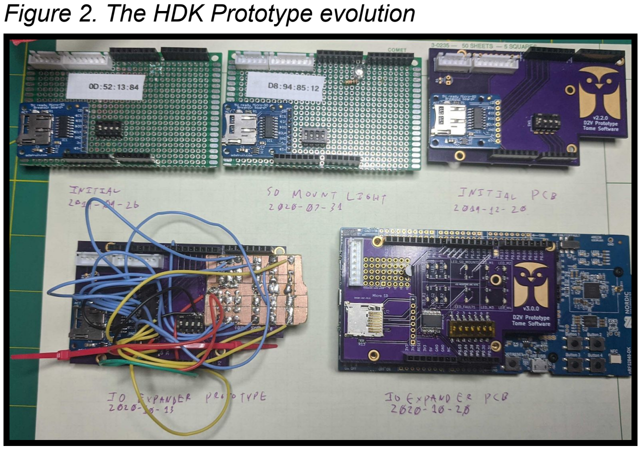
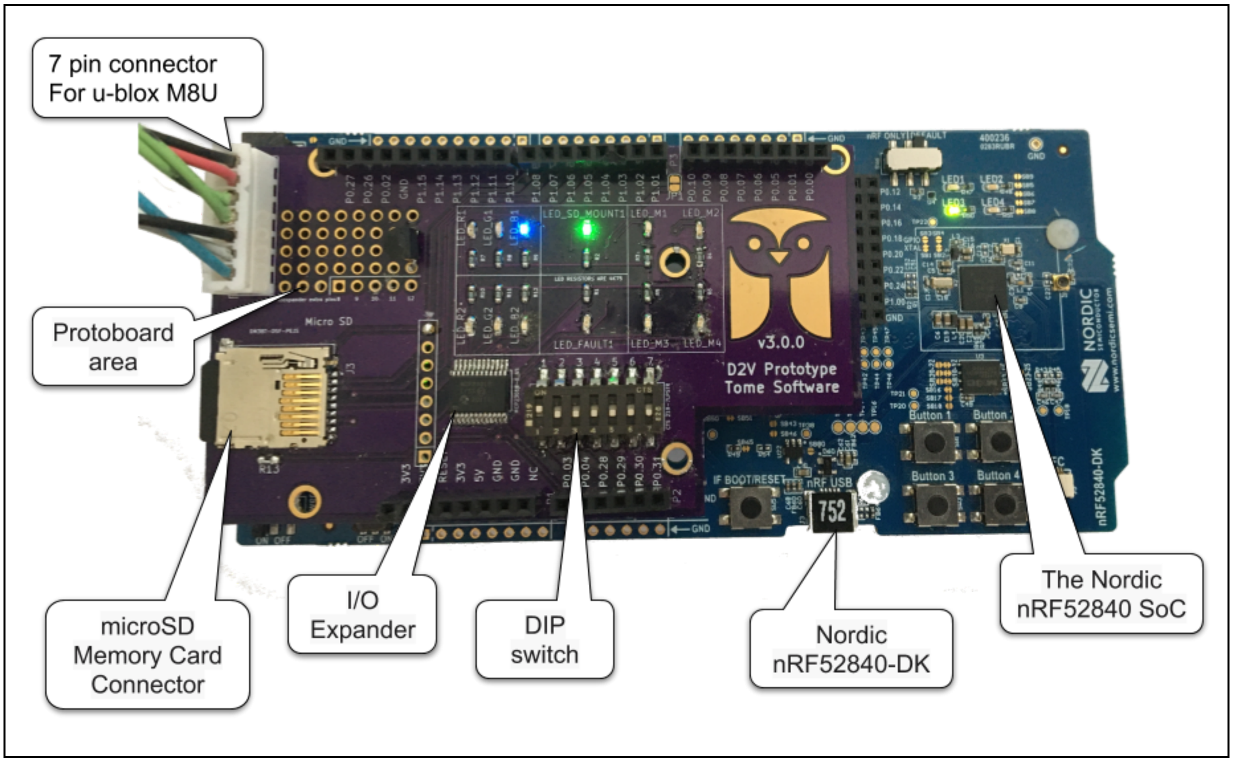


Figure 3. A running HDK v3.0.0 mounted on a Nordic nRF52840-DK.



- **The microSD card connector** was of critical importance to B2V research as an aid in testing, giving insight into naturalistic behavior, because logging the data flowing from the DK's USB port is often awkward. After all, how could one ride a bicycle or an e-scooter safely and naturally while holding a laptop that recorded the trip data? Using the ChaN FatFs SD card library, included in Nordic's freely-available SDK libraries, SD card read/write functions were added to the shared codebase. These software functions give great flexibility to control what data is written to the SD card.

  The SD card must be formatted to FAT32, and is limited to a maximum of 32GB. This limitation is because higher capacity cards would consume too many resources on the Nordic board, and this limitation is typical for embedded systems. The Nordic USB port streams the same data that is written to the SD card, should a user want to capture logging data with a laptop or other computer.

- **USB Serial output** is fed the same loggable data that flows to the SD card. The serial port being preferred for the congestion tests where the 45 DK boards made managing 45 microSD cards inconvenient. The USB Serial port is also the data source for external laptops/computers running the B2V monitor application.

- **The DIP switch** allows the user to configure the DK for sending, receiving or both; or enable a demo mode where prepared safety messages are read from the SD card and transmitted. The demo mode allows static testing and debugging when GPS satellites cannot be received. It can also be used to showcase B2V capabilities at indoor meetings and trade shows. An additional switch selects the type of message to transmit: a basic safety message (BSM), which was intended for vehicle-to-vehicle communication but has an optional field that can specify the basic type as a bicyclist; or a personal safety message (PSM) that is intended for use by VRUs.

In receiver mode, the DK automatically captures and processes both types of safety messages. The switch functions are programmable and are defined in the codebase.

- **The seven-pin connector** provides data connectivity and power between a u-blox M8 Series deduced reckoning GNSS module and the codebase running on the DK. Currently, B2V uses a u-blox EVK-M8U evaluation kit for GPS location and inertial guidance.
  As a side note, the NEO-M8U SoC incorporates a GNSS receiver able to process multiple satellite constellations and a multiple-axis inertial measurement unit that can be programmed to "use" GNSS location, speed, etc. with the IMU, giving reliable location data when traveling out of satellite reception.

  The codebase sends a set of commands to the M8U through the I2C pins and receives rapid updates to the current location/speed/altitude/time and other parameters.

  A previous experimental HDK version incorporated u-blox model NEO-M8L that required being "tethered" to sense the bicycle/scooter wheel revolutions for greater accuracy. This was deemed impracticable at present for bicycles and too invasive to rewire e-scooters to get its wheel "tick" circuitry.

- **An I/O expander chip** was added in v3.0.0 to drive eleven of the twelve programmable LEDs while conserving the DK's valuable GPIO ports. The chip is accessed through the I2C bus.

- **Twelve additional LEDs for confidence and monitoring** along with codebase functionality were added. The LEDs are intended to indicate the status of external sensors (currently the GNSS "fix" status of the connected u-blox M8U: "red" is no location fix, "blue" is satellite-only location fix, "green" is sensor fusion combining satellite and IMU). Other LEDs indicate that the SD card is mounted; spare LEDs for additional sensors or other purposes; and a favorite of the development team: a bright red "fatal software error" LED.

- **A small protoboard area** was added to allow users to add additional components for their customization projects.

- **Future HDKs may be stackable** to ingest more data sources.

HDK Use Cases

Tome uses the HDK in its everyday work on the B2V project goals and we believe it will be helpful to others in their work by logging data for testing and simulation purposes, interfacing different sensors for comparison, allowing extensions to the HDK by prototyping on top of the board, monitoring important processes, or even stacking multiple HDKs to gather more data sources.

There are many members of the B2V Working Group, two of which share their case studies that involved updating existing commercially-available products as prototypes to support the Bluetooth LE transmission of personal safety messages.

Prototype Case Study: Bontrager® Flare® RT

Figure 4. The Flare RT bike light (above left), rebuilt with B2V GNSS and Bluetooth chipset (above right).

Trek Bicycle Corporation's development of a B2V prototype has been a continuation of a larger bicycle initiative that has been ongoing over the last several years. The pursuit of getting more people using bicycles and a safer riding experience has been on the forefront of electronics aftermarket product development. Several years of research and collaboration with Clemson University's Perceptual Awareness Department has pointed Trek towards developing products that increase the range and detectability of riders. The result of the research led to Trek's *ABCs of Awareness – Always On, Biomotion and Contrast*. It is a hierarchy of what, at the time, the research showed to be the best way to be conspicuous. The first step, and relevant to this study, is "Always On" meaning using lights at all times, day or night. Within the Bontrager brand, Trek took a big step in making lights powerful enough to be used in all conditions available to the consumer with the Flare and Ion family of light models.

The continued research with the human factors experts at Clemson further refined many features of the Flare and Ion including the focus, flash and range. The focus is optimized by in-depth optics research and simulation making sure the light is directed where it will have the most impact, minimizing wasted light and ensuring an effective range to be seen, notified and safely avoided. The flash patterns are borrowed from and are tested to the same standards as emergency vehicles. The range was improved by leveraging the latest and most-efficient LED technologies and battery available. For the taillight, Flare RT, this results in a peak of a

90-lumen output. Additional features to keep the rider focused on the road include an auto-adjusting brightness feature based on ambient conditions and a wireless connection (Bluetooth/ANT+) to a Bontrager remote or Garmin computer head unit so the rider can view the light mode and battery status without having to reach back or look back at the unit while riding. All these safety features made the Flare RT a natural product to evolve for development with B2V features.

The choice of the Flare RT to create a B2V prototype wasn't just an obvious evolution based on its safety position within the Bontrager lineup: It shared a lot of electronics hardware with the components necessary to communicate within the B2V ecosystem. To create the prototype two changes were made to the hardware.

The first was to the wireless radio/microcontroller. Our original Flare RT design used the Nordic nRF52382, ubiquitous to many of the industry's ANT+/Bluetooth Low Energy products. The Flare RT B2V prototype used a product from the same family, the Nordic nRF52840, to leverage the long-range Bluetooth 5 features and benefit from the higher +8 dBm transmission power. The change within the family of products allowed for reusing much of the original code to implement features of the LED and its connectivity.

The second change was the inclusion of the U-Blox CAM-M8Q GPS module. This component allowed for quick development time while minimizing the impact to the overall volume of the taillight. The CAM-M8 series has a built-in antenna and a miniature size while maintaining sensitivity. It is anticipated that the design of the Flare RT B2V prototype will see additional design iterations once the performance of the device is fully analyzed.

The Bontrager and Tome teams were able to collaborate on the development of the prototype. The Flare RT firmware benefited from the libraries and tools established by Tome. The Flare RT utilizes the Libsm codebase to send PSMs populated by location and velocity data collected by the CAM-M8Q GPS module. Additionally, the Flare RT acts as a sensor in a Bluetooth/ANT+ ecosystem, so it must continue to send traditional Bluetooth packets to a receiver such as a bicycle computer or bicycle remote for the purposes of controlling and monitoring the light's status. Since it has to continue to act as a sensor, the device uniquely alternates between the traditional packets and the long-range Bluetooth LE transmissions (also known as Coded PHY) packets conveying the personal safety messages. The demands of testing the Flare RT prototype also required implementing the ability to configure three variables on the nRF52840: transmission rate, transmission power and disabling or enabling the Coded PHY transmission.

The Flare RT B2V prototype demonstrates a viable product that has already shown to be successful in the marketplace. It builds on a foundation of solid research and engineering that created a passive solution to building driver awareness to the cyclists. The inclusion of the B2V safety messages in the Flare RT presents an opportunity to create an active solution and build upon an ecosystem of Trek products that help keep cyclists safe.

Prototype Case Study: The Specialized Ride App with B2V

Specialized Bicycles has developed a social riding and safety app called Specialized Ride. It combines several aspects of riding into a single unified experience – meeting up for rides, chatting with other riders, mapping and recording rides, performance metrics, location tracking, time-based safety, crash detection and emergency contact notification. The goal is to integrate safety into the more enjoyable aspects of riding so that users will be able to have a safe riding experience without having to even think about it.

Figure 5. The Helmet-integrated ANGi crash sensor (left), screen capture of the Specialized Ride *app (right)*

With the Specialized Ride app, when connected to a helmet-integrated ANGi crash sensor, if a user is incapacitated in an accident, the app will notify their contacts of the situation and their location. A user can also set a time limit for their ride and notify their contacts if they do not quit their ride in sufficient time. They can also set contacts to receive ride begin and end notifications, which send links to live maps of the users on their ride.

The goals of the B2V project fit well with the overall objectives of the Ride app. Integrating B2V technology into Specialized Ride allows for additional safety features to be present without burdening the rider with more applications to run or devices to manage.

Because of Specialized Bicycle's ongoing commitment to rider safety and in order to facilitate the adoption and widespread use of B2V technologies, Specialized Bicycles created a helper library based on Tome's core technology library for Android, which allows software developers to add B2V transmission to any existing Android app with a minimum of effort. Using this helper library, the integration of B2V with the Specialized Ride app took only five lines of code. With this change, riders who use the B2V-enabled version of the Specialized Ride app will automatically have their position, heading and speed broadcast to B2V-compatible vehicles when they are on a ride.

Specialized Bicycles has contributed this helper library back to the B2V shared codebase in order to facilitate fast adoption of B2V technologies to improve rider safety on the road.

Bench Testing

Bicycle-to-vehicle (B2V) is a one-way communication using Bluetooth LE version 5.x wireless technology to inform nearby motorized vehicles of the presence of a bicycle or e-scooter. Due to its safety-critical nature, B2V communication needs to be robust and reliable for a vehicle to be "aware" in different urban and suburban environments.

An urban environment creates myriad of challenges for Bluetooth LE operation. For instance:

- Coexistence with Wi-Fi; Bluetooth wireless technology is an unlicensed service, used in the unlicensed Industrial, Scientific and Medical (ISM) band.
- Multiple other radio transmissions, such as Zigbee or Thread, operate in the same band.
- Intersections where multiple bicycles will be present and simultaneously transmitting to the vehicles.
- Vehicles and bicycles may be moving at high speed relative to each other.

Even with all these challenges, vehicles need to be aware of a bicycle at a certain (30-120 meters) range. To evaluate the reliability and coexistence performance of Bluetooth LE 5.x transmissions (so that it can meet the B2V requirement), three major tests are performed: range, interference and congestion.
In each of these tests, the Bluetooth LE 5.x broadcaster ("sender") and observers ("receivers") operate in non-paired mode and the observers are scanning continuously.
The other parameters that are configured in the test cases are transmission power, advertising interval, payload size, PHY layer (coded or uncoded), scanning window and scanning interval. Based on the discrete values chosen for each of these parameters, more than 1,200 binary test configuration files are generated and a subset is selected for each of the primary tests. Prior to a test, the selected test configuration file is uploaded to the many broadcasters *en masse*.

Range

The goal of the range test is to find the maximum range of Bluetooth LE 5.x transmissions in different wireless conditions. The tests were performed to create graphs showing the relationship between range and transmit power, payload size and PHY. To understand observer and broadcaster device performance, each of the tests is run at different attenuations and dynamic maximum attenuations to find the receive sensitivity at the maximum range.

Interference

The interference tests are conducted to understand Bluetooth LE 5.x performance and coexistence in the presence of noise and other interfering signals. Bluetooth LE transmissions operate in an unlicensed band, where any device can transmit subject to certain rules. It is expected that during B2V operation, Wi-Fi at 2.4 GHz and other radios can hinder packet reception through keeping the channel occupied. Therefore, in our rigorous interference and coexistence tests, we have considered Bluetooth LE 5.x PHY performance for different payload sizes and in different interference scenarios. The interference test plan follows Bluetooth SIG and IEEE/ANSI recommendations for Bluetooth LE reliability studies (IEEE/ANSI 63.27-2017). Assuming the observer as being an in-vehicle device or a TCU, bench tests are set up to introduce significant Wi-Fi and white noise interference to the observer. There are also coexistence studies conducted introducing legacy Bluetooth, Bluetooth LE and continuous wave signals in co-and-adjacent channels to hinder intended Bluetooth LE reception.

Congestion

Congestion tests are performed to understand communication performance in scenarios, where multiple bicycles in an intersection are simultaneously transmitting to the receiver/observer in the vehicle. These particular tests are performed in a rigorous fashion with up to 45 physical broadcasters and 1 observer. A Keysight Propsim F64 channel emulator has been used to emulate many-to-one broadcast setup. The scope of congestion tests encompass B2V devices sharing and occupying the Bluetooth LE advertising and data channels (80 MHz, 40 channels) simultaneously for a defined payload size of up to 255 bytes. The tests are thus performed based on changing the timing configurations (advertising interval, scan interval and scan window) along with changing the PHY.

A description of the test procedures and techniques can be read in Appendix A.

Research Next Steps

Analysis and Recommendations per Indoor Lab Tests

The data collected during the indoor lab tests is currently being analyzed. The analysis will help determine if certain configurations of the software perform better in different scenarios, and what use cases can be supported. This will aid in determining hardware, software and power requirements. A report out of the recommendations per the indoor lab tests is anticipated in early 2021.

Outdoor Field Tests

Outdoor field tests are expected to be performed in Q1/Q2 2021. These tests will include range, interference and congestion tests with similar KPIs as the indoor lab tests performed in 2020. The test location will be Wi-Fi free to create a baseline for comparison. Wi-Fi and Bluetooth wireless technology will be added to the environment to enable congestion and interference testing. Additional testing will introduce automobile, bicycle and e-scooter interactions with line of sight (LOS) and non-line of sight (NLOS) tests performed using an obstruction to represent real world scenarios. This will also provide insight as to how device placement on the vehicle or human body affects message transmission.

Pilots

A pilot phase will follow the outdoor field tests. This will include one or more pilots likely partnering with academia and/or cities and municipalities for testing the prototypes in an environment with more users and for a longer period of time. This will enable data to be collected and evaluated. Data evaluation will include confirming B2V performance requirements and the sensor performance itself, and may provide insight into scooterist and cyclist dynamics and behaviors in a given scenario. It is expected that this data could also be used as input to simulation environments, such as average speed or acceleration rates.

HDK

Additional development of the HDK prototype will continue in 2021. This will include further review and integration of a base sensor set that meets the minimum performance requirements for a cyclist VRU. We will also continue research of RF solutions for BSM/PSM transmission and integration within the HDK. In addition, we are also evaluating centralized data storage and retrieval options of the transmitted and received messages for simplifying the data collection and analysis process.

Security Evaluation

In 2021, we will evaluate security requirements for the transmission of the safety messages, ensuring not only the integrity of the data, but also the availability and confidentiality of the transmitted and received messages. This evaluation will also encompass authenticity and message requirements to prevent spoofing attempts. These security requirements will be evaluated for both the bicycle (sender) and the vehicle (receiver).

Appendix A

Background to Testing

For low and medium data rate applications such as listening to music or file transfers, Bluetooth wireless technology in many devices (e.g. phones, tablets, computers) has been coexisting alongside Wi-Fi in the same 2.4 GHz spectrum. The coexistence is possible due to the nature of Bluetooth radio design. Bluetooth channels are spread across the entire 80 MHz spectrum with multiple non-overlapping channels. Legacy Bluetooth devices operate on seventy-nine 1 MHz wide channels whereas, newer Bluetooth LE devices occupy forty 2 MHz wide channels along the band. Multiple Bluetooth LE and legacy Bluetooth devices can coexist in the same band as they can hop among channels to find the least interfered channel for data transmission. This adaptive frequency hopping makes Bluetooth wireless technology a reliable point-to-point protocol.

For bicycle to vehicle communications, Bluetooth LE wireless technology may provide similar reliability and robustness. At this point, we assume that the B2V devices will be broadcasting advertisements with maximum payload of up to 255 bytes, transmitted every 100ms. B2V devices also need to make the vehicles aware of the bicycle from a significant distance (30-150 meters). This translates to a need for higher transmit power, better receive sensitivity, better radio designs with a higher tolerance to outdoor noise/interference in the same band, channel coding, etc. Bluetooth LE 5.x addresses this issue with the introduction of Coded PHY, which is purported to provide better range and reception performance for a similar payload compared to its uncoded counterpart.

It is clear that unwanted signal and channel noise can create significant challenges for reliable Bluetooth/Bluetooth LE communication. Moreover, Bluetooth wireless technology operates on an unlicensed spectrum which is open for Industrial, Scientific and Medical (ISM) use. In a later section we introduce the challenges in operating within that unlicensed spectrum.

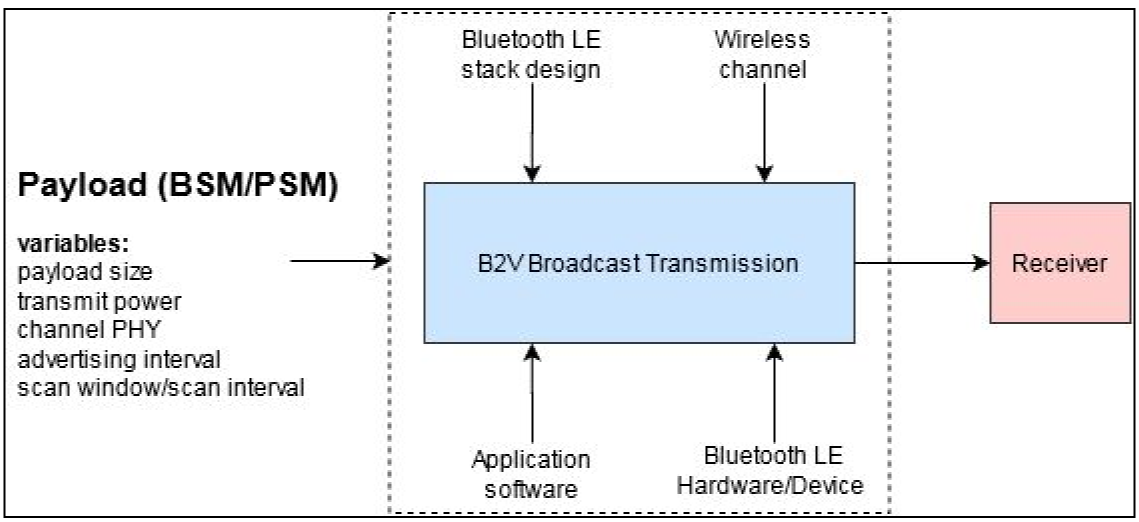
Bluetooth Wireless Technology Testing

All the B2V applications mentioned above rely on the successful broadcast message (BSM and PSM) transmissions. This is an open loop (one-way) communication design, where no notification will return to the bicycle from the vehicle that a transmission was successful or unsuccessful. Therefore, the only way to guarantee the reliable, one-way communication is to test the system with the input and interacting parameters.

The goal of Bluetooth testing is to determine a combination of values for the variables, so that it is possible to overcome the effect of outdoor wireless channel transmissions, if possible.

To test the integrity of the system itself, the first objective is to find the input variables of the system. The second goal is to identify other controllable and uncontrollable interacting elements. The third objective is to determine how the interactions can be captured quantifiably, to measure the reception performance.

Figure 6. The variables and other factors that may interact with the reception performance.



In terms of Bluetooth wireless technology testing, the scope is limited to reception performance with respect to:

- Variables involving the Bluetooth LE transmitter/receiver (i.e. payload size, transmit power, channel PHY, advertising interval and continuous scanning with scan interval/window).
- Wireless channel in terms of fading, interference, etc.

Wireless packet reception at the end-device depends on the channel quality, which can detrimentally affect the signal quality.

Channel quality is dependent on signal propagation environment (blockages, line of sight, multi-path due to objects between transmitter and receiver, etc.), distance between transmitter and receiver, the presence of other unwanted radio signals blocking or interrupting the wanted signal, etc. Guaranteeing radio reception in this one-way system design depends on observing Bluetooth LE performance with respect to a detrimental wireless environment.

Challenges in an Unlicensed Band

Unlicensed spectrum means a chunk of radio resources available to the public for free, given the devices operate within FCC limited effective isotropic radiated power (EIRP). Bluetooth LE transmissions operate within an unlicensed 2.4 GHz spectrum, which means it must coexist with all other radio protocols that operate in the same spectrum, along with spurious transmissions from different devices in the vicinity or unwanted interruption from hobbyist use of the spectrum. Unlicensed 2.4 GHz spectrum is shared by Wi-Fi, existing Bluetooth wireless technologies, Thread, Ant+, Zigbee and multiple other radio protocols. Along with all other radios, there could be spurious and unwanted signals that can interrupt broadcast transmissions. Therefore, reliability of the Bluetooth broadcast depends on its nonsusceptibility to the expected presence of noise and interference in the unlicensed band.

Though there are multiple radios that can operate in the same spectrum, i.e. Thread, Zigbee, etc., most of the band is occupied by 802.11 a/b/g/n Wi-Fi transmission because of its widespread use. There are eleven 20 MHz Wi-Fi channels in the 2.4 GHz band. For Wi-Fi transmissions, three non-overlapping channels are often selected.One such combination is 1, 6 and 11 that is largely used to configure Wi-Fi devices in the U.S. However, users can also select any channel from the pool of 14 channels to configure their devices and transmit.

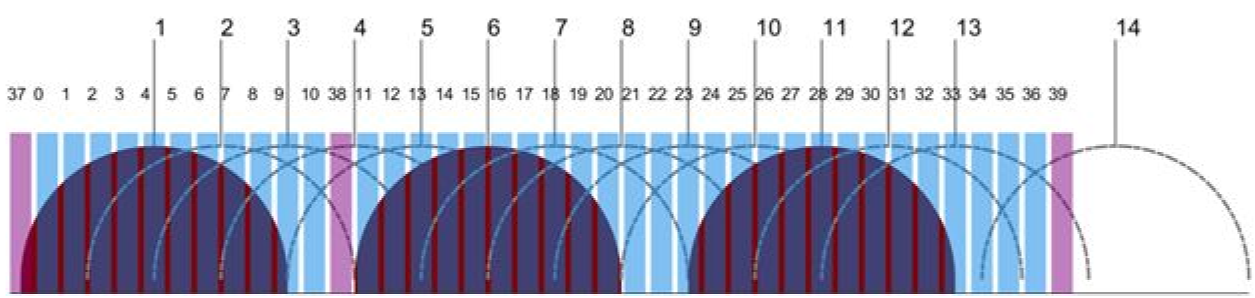


Figure 7. The spectrum of fourteen Wi-Fi channels coexisting with 40 Bluetooth channels.

B2V applications using Bluetooth LE can experience interference at the end device, as Wi-Fi transmissions from thousands of access points running at restaurants, hospitals, campuses, shops and city centers and smart devices, along with in-vehicle hotspots can adversely affect the reception.

Coexistence

Though it appears sufficiently challenging for Bluetooth LE transmissions to operate alongside Wi-Fi, in our regular everyday use Bluetooth LE transmissions work reliably to provide a personal network experience (audio, music, health information, etc.). The reliability of Bluetooth LE wireless technology comes from the design of the radio itself with adaptive frequency hopping, Bluetooth LE advertising channels (37, 38, 39) being mostly unaffected by the Wi-Fi channels, and it works opportunistically and reliably, providing an excellent personal experience to the indoor user.

However, B2V applications are used outdoors, where the vehicles need to be aware of the bicycles within a certain range (30-150 meters). This range requirement introduces additional challenges to the B2V applications supported by Bluetooth LE technology.

Therefore, the B2V application must support the distance requirement:

- In different mobile wireless environments (city, open sky, rural) at different velocities.
- With multiple B2V devices simultaneously occupying the Bluetooth LE channels.
- With Wi-Fi and other signals interfering with communication.

To better understand the performance of B2V communication, we conducted bench tests for Bluetooth/Bluetooth LE wireless technology with the Nordic HDKs. There are three major tests performed: range, interference, and congestion. In each of these tests, the Bluetooth LE 5.x broadcaster and observers will be operating in non-paired mode and observers will be scanning continuously. The other parameters that are considered to configure the test cases are transmission power, advertising interval, payload size, PHY (coded, uncoded), scanning window and scanning interval. Based on the discrete values chosen for each of these parameters, more than 1,200 binary test configuration files are generated and selected for each of the primary tests. Prior to a test, the selected test configuration file is uploaded to the many broadcasters en masse.

Bench Tests

Bench tests are a standard way to conduct repeatable wireless tests. In the real world, wireless environments vary drastically, which does not translate to conducting over-the-air repeatable tests. Thus, all the tests are conducted as bench tests to thoroughly understand Bluetooth LE performance in simulated or emulated wireless environments and conditions. While designing the test cases, we followed the recommendation from the IEEE/ANSI 63.27-2017 standard to follow industry compliance in addressing reliability.

Key Performance Indices (KPI)

Each test case is analyzed based on certain key performance indices (KPI) to quantify Bluetooth LE performance in those individual scenarios. They are as follows:

Received Signal Quality Indicator (RSSI)

RSSI signifies the channel quality. Based on the RSSI value, it is possible to understand the channel condition and estimate the distance between transmitter and receiver.

Receivers may receive low RSSI values for the following conditions:

- Distance
- Non-line-of-sight
- Blocking enclosures (receiver/antenna being in-vehicle, the human body blocking signals, etc.)
- Mobility, multi-path and the like

Packet Loss/Drop Rate (PLR)

Packet loss/drop rate depends on how many packets are being dropped within a certain time period. For example, if there are 10 packets to be received within a 1 second period and only seven of them are received, three packets were lost during transmission. This indicates a 30% packet loss rate. Higher packet loss/drop rate means higher interference, higher number of channels being already occupied or lower channel quality. Therefore, packet loss/drop rate provides information about Bluetooth LE reliability in a scenario.

Inter-packet Gap (IPG)

Inter-packet gap (IPG) is defined by the interarrival times of the packets at the receiver. IPG is measured by the difference between arrival timestamps of two consecutive good packets. IPG is directly related to the advertising interval and packet loss/drop rate of the transmission. Higher values of IPG result in receivers or the vehicles receiving delayed updates from the bicycle. A delayed location/heading update from the bicycle can be challenging for a driver who must make a timely and informed maneuver.
For example, in the figure below, packet with Sequence ID #42 was not received, leading to an IPG of 207ms (4172ms - 3965ms), where the advertising interval was set to 100ms.

Figure 8. The measurement of IPG from a missing packet.

MAC ID	***CONFIG***	***Time***	***Sequence ID***	***RSSI***	***RF Channel ID***
E2:EB:9D:B3:F7:3F	131	3965	41	-68	34
E2:EB:9D:B3:F7:3F	131	4172	43	-68	6

Once KPIs and test cases are defined, it is also important to identify the combinations of parameters that will be running for range, interference and congestion tests. The overall combinations used to configure the devices are shown in the table.

Therefore, the total number of test cases depends on the number of configurations for each subtest, number of subtests under a major test, number of test devices and finally, the number of major tests.

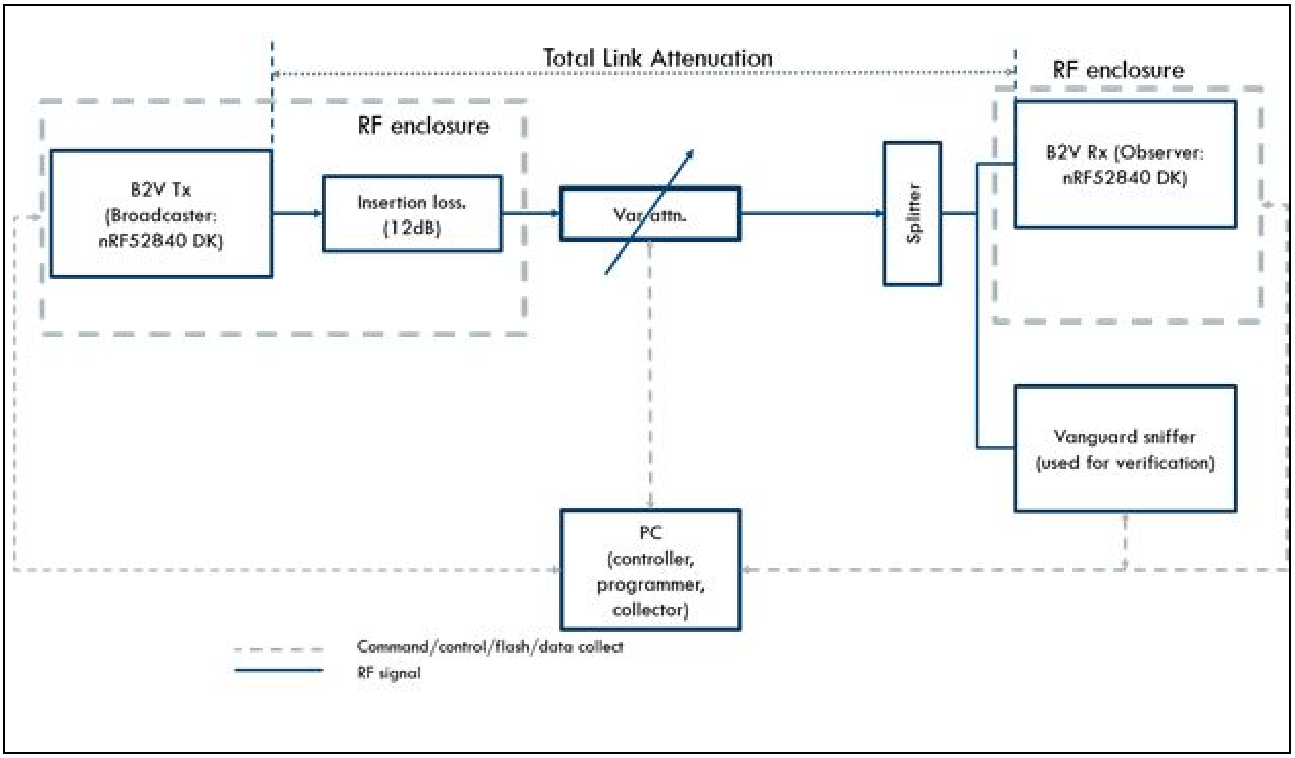
The following section discusses each major test and how they are performed in the labs.

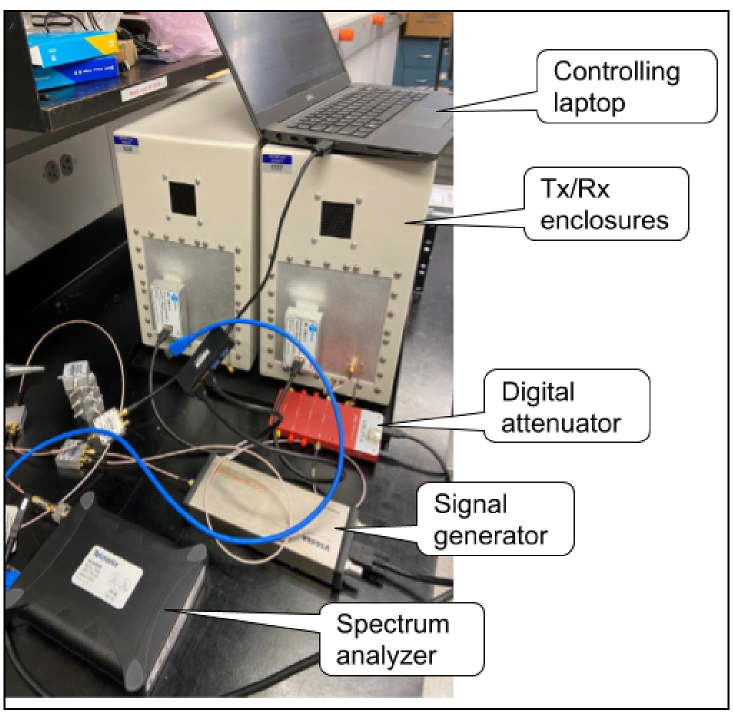
Figure 9. The combination of test parameters.

Device	***Device parameters***	***Values***
Broadcaster	Advertising intervals	Nx100ms and 20ms
Broadcaster/Observer	PDU sizes	~30, 100, 200 bytes
Broadcaster/Observer	Advertising channels	**37, 38, 39**
Broadcaster/Observer	Advertising data channels	**0-36**
Broadcaster	Transmit power	-8 to +8dBm (linear scaling with 4dB interval)
Observer	Scanning window	100ms-1000s
Observer	Scanning interval	(equal to scanning window)
Observer	Receiver sensitivity	-95 dBm (LE1M) and -103dBm (LE125K)
Observer	RSSI readings (+/- 2dB)	-20 to -90 dBm

Range Testing

Figure 10. A block diagram of the bench test setup (immediately below) and the lab setup (bottom of page).





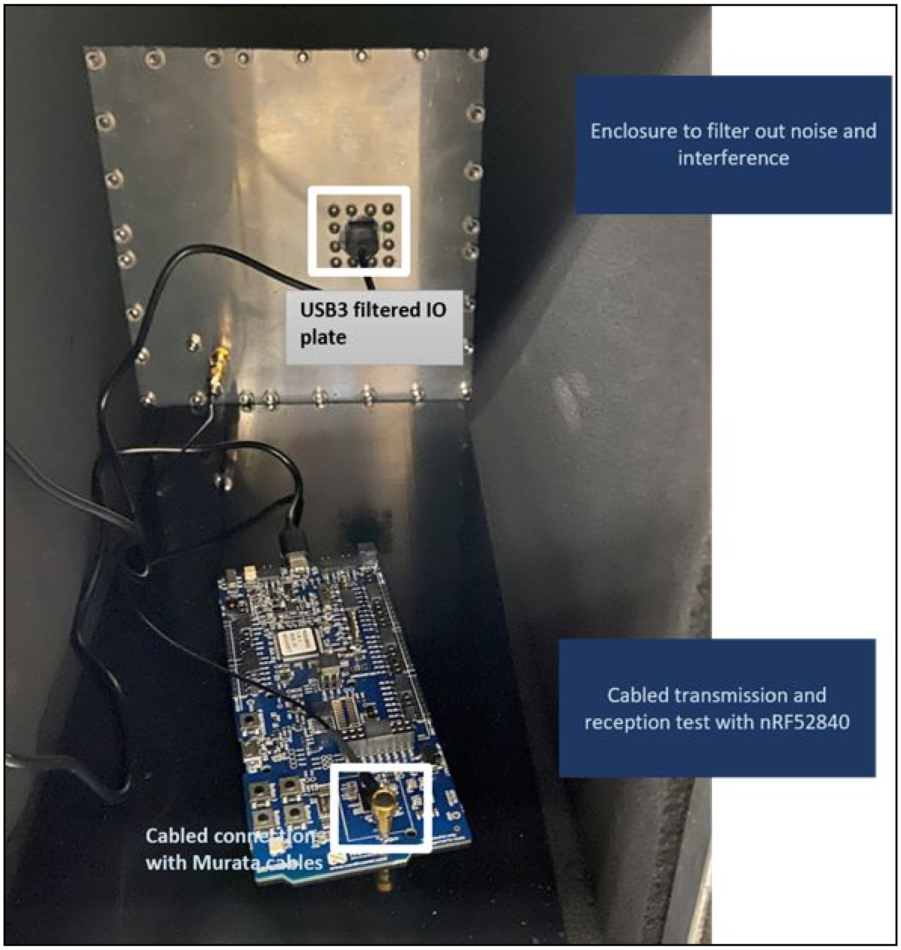
The goal of the range test is to find the maximum range of Bluetooth LE 5.x in different wireless conditions. The tests are performed to find maximum range at different transmission power, payload size and PHY. To understand observer and broadcaster device performance, each test is run at different attenuations and dynamic maximum attenuations to find the receive sensitivity at the maximum range. The attenuations are calculated based on the B2V range requirements and programmed with digital attenuators. Overall range has been estimated based on each calculated link budget and numerous mathematical models (Okamura-Hata, COST-231, Free Space, etc.).

Figure 11. The parameters used for running the Range tests.

Parameters	***Value***
# of configurations (hex files)	24
Run time	60s/iterations
Tx power	-8:4:8 dBm (LE1M and for <= 30m) and 0:4:8dBm(LE1M, LE125K, >=30m)
Advertising interval	100ms
Scanning interval	100ms
Payload size	30, 100, 255 bytes
PHY	LE1M, LE125K *Note: LE125K is "Coded PHY"*
Attenuations	70, 76, 79, 82 dB (FSPL at 30-120 meters distance) + receive sensitivity tests

Interference Testing

Figure 12. A view inside the RF enclosure.



The interference tests are conducted to understand Bluetooth LE 5.x performance in the presence of noise and other interfering signals present. Bluetooth LE operates in an unlicensed band, where any device can transmit subject to certain rules. It is expected that during B2V operation, Wi-Fi at 2.4 GHz and other radios can hinder packet reception through keeping the channel occupied. Therefore, in our rigorous interference and coexistence tests, we have considered Bluetooth LE 5.x PHY performance for different payload sizes and in different interference scenarios. The interference test plan follows Bluetooth SIG and IEEE/ANSI recommendations for Bluetooth LE reliability studies (IEEE/ANSI 63.27-2017).

Assuming the observer is an in-vehicle device or a TCU, bench tests are set up to introduce significant Wi-Fi and white noise interference to the observer. There are also coexistence tests conducted, introducing legacy Bluetooth, Bluetooth LE and continuous wave signals in co-and-adjacent channels to hinder intended Bluetooth LE reception.

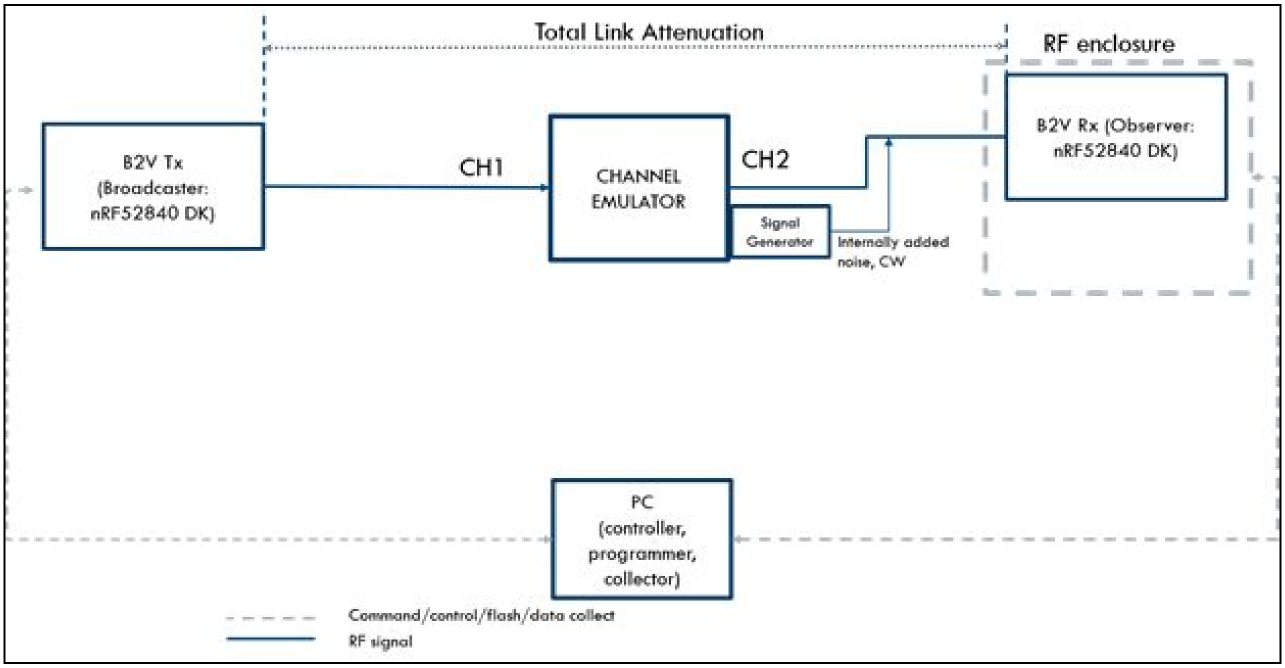


Figure 13. The block diagram for bench test and channel emulator based setups.

To understand Bluetooth LE reliability, the following tests are run in the bench test setup:

1. Cabled transmission and reception tests with added channel impairment (noise).
    a. With only noise on advertising channels.
    b. With noise on half of the total 80 MHz spectrum.
    c. With noise on the entire spectrum.
2. Cabled transmission and reception tests with simulated external interference with continuous wave.
    a. With continuous wave spreading over the entire spectrum.
3. Cabled transmission and reception tests to observe co-existence with Wi-Fi overlapping and proximity channels.
4. Cabled transmission and reception tests to observe coexistence with Bluetooth LE LE1M blocking the advertising channels.
5. Cabled transmission and reception tests to observe coexistence with the recorded real-world noise and interference.

Figure 14. The parameters for Bluetooth LE interference tests.

Parameters	***Value***
# of configurations (hex files)	6
Run time	10s/iterations
Tx power	0 dBm
Advertising interval	100ms
Scanning interval	100ms
Payload size	30, 100, 255 bytes
PHY	LE1M, LE125K
Attenuations	66 (channel emulator) and 76 (bench) dB

Congestion Testing

Thus far, the tests are mostly one-to-one tests, which means there is only one transmitter and one receiver device under test. In the real world, there would be many bicycles simultaneously broadcasting to nearby cars. In this particular scenario, Bluetooth LE enabled B2V devices will be sharing available Bluetooth LE data and advertising channels leading to packet collisions and subsequent packet drops. When sending a payload of 255 bytes, Bluetooth LE devices use both advertising (ADV_EXT_IND) and data channels (AUX_ADV_IND), occupying the channel for some amount of time. During this time period, if another device tries to access the channel, that would create congestion in that channel.

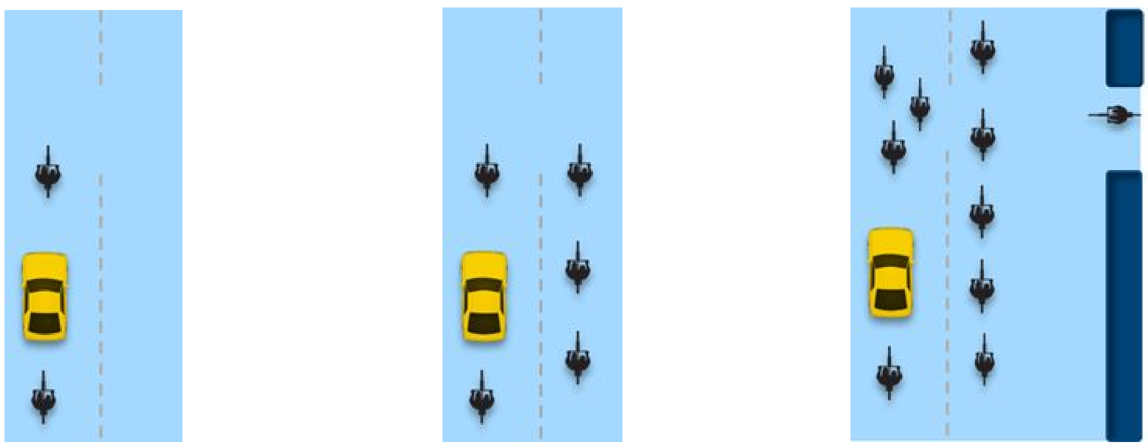
Designing a congestion test in a lab environment is complex, as it is hard to capture the real-world environment and accurately mimic it in the lab. There are multiple factors that influence Bluetooth LE congestion test design in a lab environment. They are the following:

1. The bicycles in a congestion scenario can be more densely packed (i.e. a peloton).
2. Bicycles can also be on the sidewalks, extending the simulation environment.

3. Attenuations or channel designs for bicycles should be emulated differently compared to a vehicle.
4. Lower transmission power.
5. Number of narrower channels available for Bluetooth transmissions

Congestion tests are designed considering the above factors to mimic a scenario shown below for different numbers of Bluetooth enabled B2V devices. The number of bicycles and patterns presented below might seem unrealistic. However, the goal is to test Bluetooth performance to support a safety-critical B2V application. The congestion test thus tests robustness of the Bluetooth LE 5.x wireless technology.

Figure 15. Three congestion scenarios with differing numbers of B2V devices with Bluetooth transmission enabled.



In summary, congestion tests are performed to understand performance in scenarios, such as where multiple bicycles in an intersection simultaneously transmit to the receiver/observer in-vehicle. These particular tests are performed in a rigorous fashion with up to 45 physical broadcasters and one observer. A channel emulator (a Keysight PROPSIM F64) has been used to introduce urban channel conditions and emulate many-to-one broadcast setup. The scope of congestion tests encompass B2V devices sharing and occupying the Bluetooth LE advertising and data channels (80 MHz, 40 channels) simultaneously for a BSM payload size of up to 255 bytes. The tests are performed based on changing the timing configurations: advertising interval, scan interval and scan window, and changing the PHY.

Figure 16. Looking from above at the two receivers and 46 senders set up for the congestion tests.

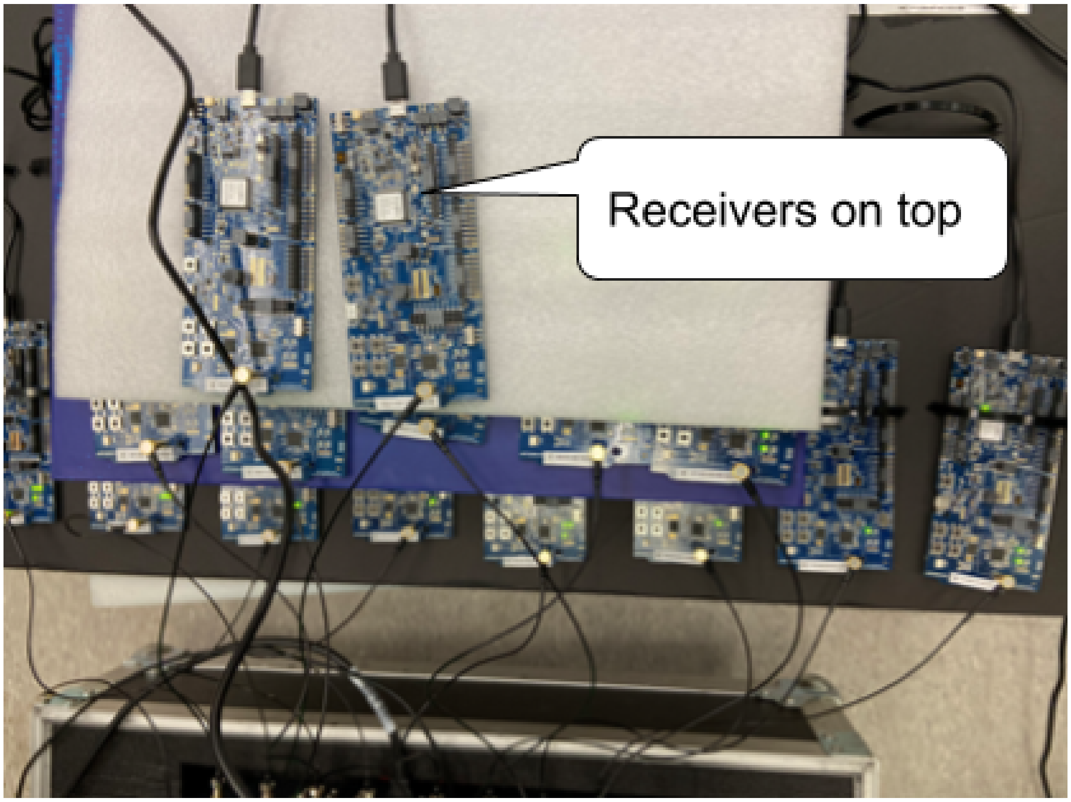


Figure 17. Block diagram of the congestion tests setup.

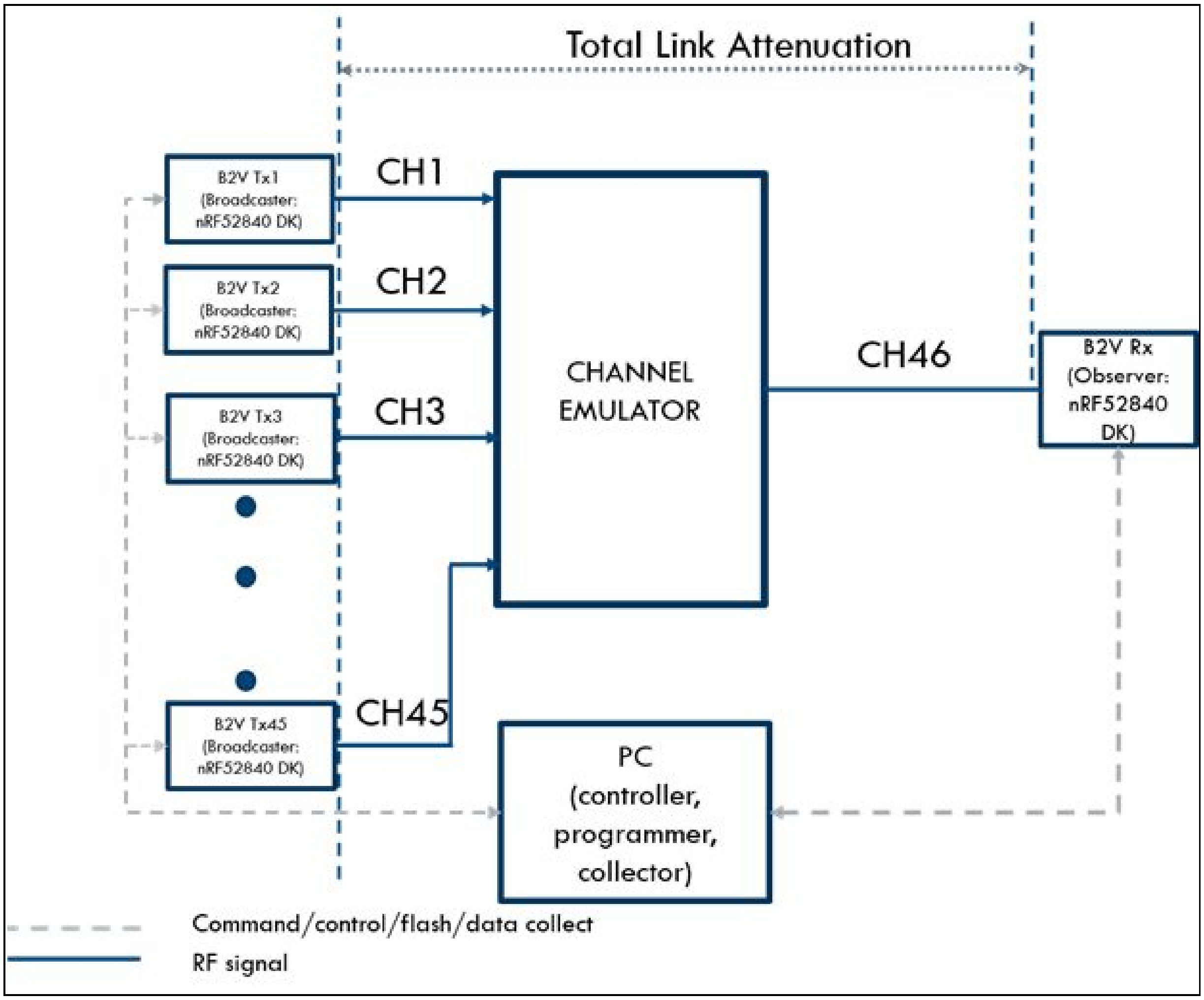


Figure 18. View of the congestion setup showing the lab hardware.

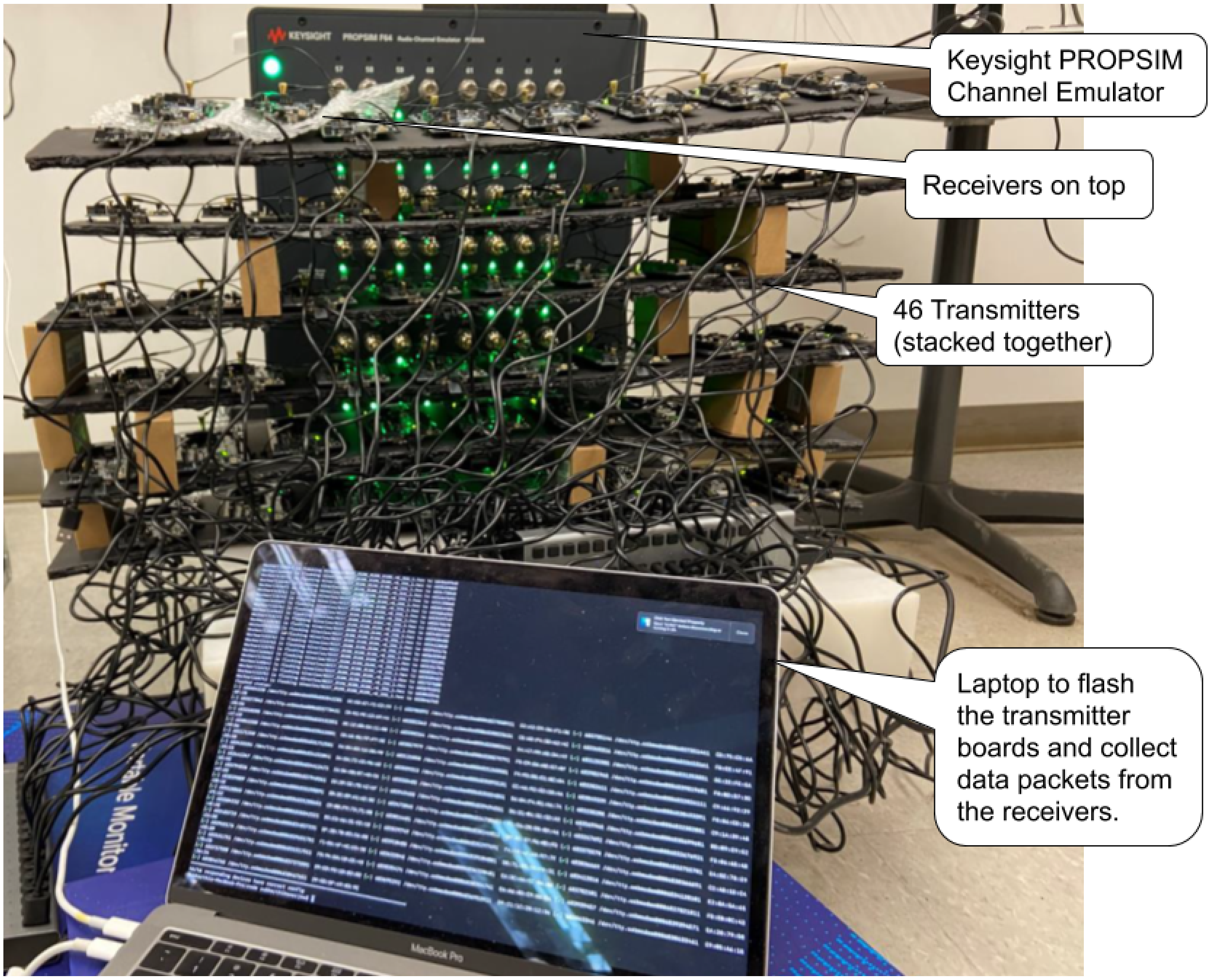


Figure 19. The parameters used in the congestion test.

Parameters	***Value***
# of configurations (hex files)	72
Run time	60s/iterations
Tx power	0 dBm (LE1M, LE125K)
Advertising interval	20, 100, 200, 300, 500, 1000 ms
Scanning interval	30, 100, 200, 300, 500, 1000 ms

Parameters	***Value***
Payload size	255 bytes
PHY	LE1M, LE125K
Attenuations	66 dB
# of devices in each test	[2, 5, 10, 15, 20, 25, 30, 35, 40, 45]
Channel model	Static 0 deg