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Development and Validation of a Measurement System for Vehicle Infotainment Bluetooth Classic Performance

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Abstract: In-vehicle infotainment (IVI) systems are critical to the modern driving experience, with Bluetooth connectivity for smartphones being a key feature for both functionality and safety. This study proposes and validates a measurement system to quantify Bluetooth signal strength between a Ford SYNC3 IVI unit and an ESP32 microcontroller in a controlled, open-air environment. The goal is to establish a reliable performance baseline for future vehicle evaluation. The methodology emphasized reliability, repeatability, and reproducibility by employing two IVI modules, two ESP32 microcontrollers, and two operators to collect data at distances ranging from 0.01m to 10m. Results demonstrated a predictable signal attenuation conforming to the Log-distance Path Loss Model and confirmed the high consistency of the measurement system across different hardware and operators. This work provides a validated data baseline that can be used to create a model for defining design requirements and, as a practical application, to identify defective IVI units before vehicle assembly, thereby reducing potential manufacturing costs.
Keywords: Vehicle Infotainment, Bluetooth Classic, Performance, MSA, RSSI.
Abbreviations: MSA, Measurement System Analysis. RSSI, Received Signal Strength Indicator.

1. Introduction

World car travel is expected to triple between 1990 and 2050. The experience of the car journey makes the other modes of travel inflexible and fragmented. Having a vehicle is the major item of individual consumption after housing. Vehicles provide autonomy to decide when and where to go that only a car can give [1].

An in-vehicle infotainment (IVI) is a system that integrates the entertainment system with the objective of facilitating a better form of driving experience. A typical infotainment system consists of audio as well as video interfaces and touchscreen [2]. In recent years the number of cars on the road with manufacturers installed IVI increased dramatically [3]. One of the main features of the IVI is to connect the user phone to the IVI through Bluetooth technology mainly to use the audio system of the vehicle to stream audio and make phone calls [4].

Bluetooth technology emerged from the need for small data exchange without using cables and with low power consumption. It has become widely adopted by vehicle manufacturers because of the low cost of the components and that almost every smartphone has this technology [5].

As smartphones features improve and expands, individuals are becoming ever more attached to their devices and the services they provide. This means that having access to those features through the IVI is extremely important to the consumer. By providing such interaction, car manufacturers play an active role in reducing the number of accidents associated with mobile phone usage while driving [6].

The present study proposes to measure and validate the Bluetooth signal strength between an IVI system and an ESP32 microcontroller in a controlled environment. The aim is for this data to serve as a baseline for subsequent measurements in vehicles to identify if Bluetooth is performing as expected by design.

2. Methodology

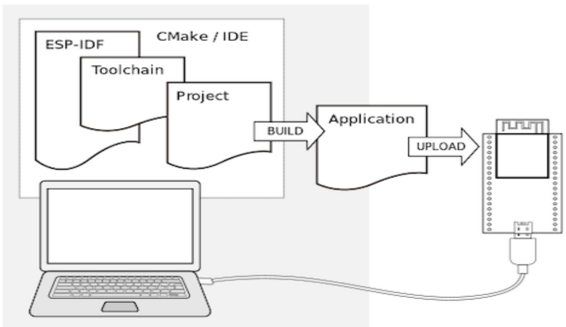
An experiment was conducted to measure how the signal strength of a Bluetooth Classic communication between an automotive infotainment unit (Ford SYNC3) and an ESP32-based receiver behaves in an environment with no significant physical barriers, though it may still contain electromagnetic interference.

To operate the IVI system outside of a vehicular environment, a Ford Motor Company SYNC3 Technical Development Kit (TDK) was used (Figure 1). It is possible to power on the TDK with the module outside of its standard enclosure, thus allowing the Bluetooth technology to operate in a free space environment.

Figure 1. Technical Development Kit

To enable the ESP32 to communicate with the TDK, an algorithm was developed in the C language so that the microcontroller could capture the signal power level. For this, it was necessary to set up the software development environment from Espressif, the company responsible for the design of the open-source ESP32 device (Figure 2). To write an algorithm specific to Bluetooth Classic, it was also necessary to configure the open-source BTstack framework from the company BlueKitchen.

Figure 2. Process to install the framework software to the microcontroller



It is needed to provide reliability, repeatability and reproducibility to the data-generating process. Quantifying and reporting these three facets with appropriate confidence intervals provides an explicit gauge of how much trust can be placed in the observed values and the conclusions [7].

Since radio communication is highly sensitive to interference, the algorithm was enhanced to capture 30 signal strength samples; these samples were then averaged to obtain a reliable value. To ensure the repeatability and reproducibility of the measurement system, two SYNC3 modules (SYNC3 3.0 with software 18093_DEVTEST and SYNC3 3.4 with software 19101_DEVTEST), two ESP32 microcontrollers (rev.1 chip ID: 2809024 and rev.2 chip ID: 16545708), and two operators were used (Figure 3). Measurements were taken at a height of 1.4 meters and at straight-line distances of 0.01, 2.5, 5, 7.5, and 10 meters. This resulted in 8 (2 x 2 x 2) independent combinations per distance and 1200 (8 x 5 x 30) total samples.

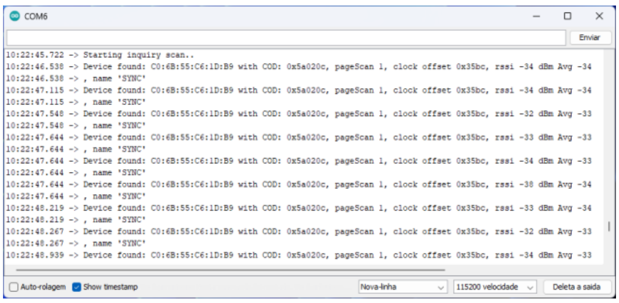
Figure 3. Modules and microcontrollers used in the experiment.

According to the manufacturer the ESP32's signal strength values can be from -10 (representing the strongest signal) to -100 (representing the weakest signal). To provide energy for the microcontroller it was connected to a laptop via a USB cable (Figure 4).

Figure 4. ESP32 connected to the laptop through the USB port

To have access to the collected data the terminal feature of the Arduino IDE software was utilized, with the data being sent through serial communication (Figure 5).

Figure 5. Arduino IDE terminal output



3. Results and Discussion

Table 1 shows the summary of the data collected using the defined measurement system recording the maximum (Max), minimum (Min), and average signal strength (120 samples for each average) in dBm (decibel-milliwatts), along with the signal variance (Var in %). For each distance we have the combined values of measurements from person 1, person 2, ESP32 rev.1 and ESP32 rev.3.

Table 1. Summary of the data collected

	Distance (m)	Max (dBm)	Min (dBm)	Var (%)	Average (dBm)
SYNC 3.0	0.01	-14	-21	7,8%	-17,5
	2.5	-47	-70	25,6%	-58,5
	5	-52	-82	33,3%	-66,0
	7.5	-59	-84	27,8%	-67,3
	10	-60	-84	26,7%	-68,5
SYNC 3.4	0.01	-13	-21	8,9%	-17,0
	2.5	-50	-74	26,7%	-60,3
	5	-51	-83	35,6%	-64,8
	7.5	-59	-82	25,6%	-67,0
	10	-60	-84	26,7%	-69,3

As shown on Table 1, at the shortest distance of 0.01m, average signal strengths were relatively high, with SYNC 3.0 at -17.5 dBm and SYNC 3.4 at -17.0 dBm. As distance increased to 10m, the average signal strength significantly decreased, reaching -68.5 dBm for SYNC 3.0 and -69.3 dBm for SYNC 3.4. This demonstrates the typical path loss experienced by wireless signals.

At 10m the system is at its limits to start failing to deliver a good data exchange since it is expected to have a significant package loss below -70 dBm [8].

The variation at close range (less than 10%) compared with the other distances, except at 5m, (around 26%) show how sensitive to interference the radio wave is. At the distance of 5m the variation was higher (around 34%) because there was electric equipment (that it was not authorized to be removed) on the left side acting as a blocker for the correct propagation of the electromagnetic wave.

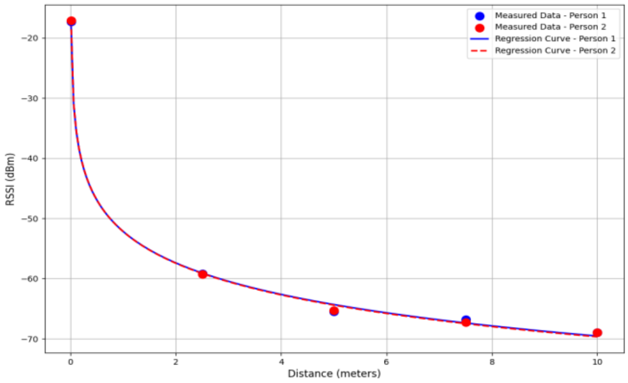
To estimate the RSSI at distances where direct measurements were not taken, it was used the Log-distance Path Loss Mode. The equation below demonstrates how the values are calculated:

$$RSSI(dBm) = RSSI_0(dBm) - 10 \cdot n \cdot \log 10\left(\frac{d}{d_0}\right) \qquad (1)$$

The process begins with a calibration phase, where empirical RSSI values are collected at a set of known distances from the transmitter. These measurements are fitted to the model, which establishes a linear relationship between RSSI (in dBm) and the base-10 logarithm of the distance. This regression analysis determines the key environmental parameters of the model: the path loss exponent (n), which describes the rate of signal decay, and the reference $RSSI_0$ at a close-in distance (0.01m). The path loss exponent was calibrated for free space environment (n=2), the resulting equation provides a continuous function that can reliably interpolate or extrapolate to predict the expected RSSI value at any given distance within the model's effective range, thus enabling the creation of a complete signal coverage map from a limited set of empirical data points [9].

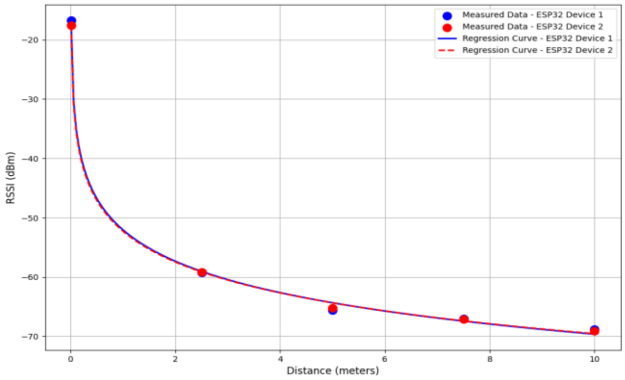
Measurements performed independently by two individuals, Person 1 and Person 2, produced results that were not statistically different, demonstrating a high degree of consistency and minimizing the potential for operator-specific bias (Graphic 1).

Graphic 1. Comparison of Logarithmic Regressions for RSSI vs. Distance from Person 1 and Person 2



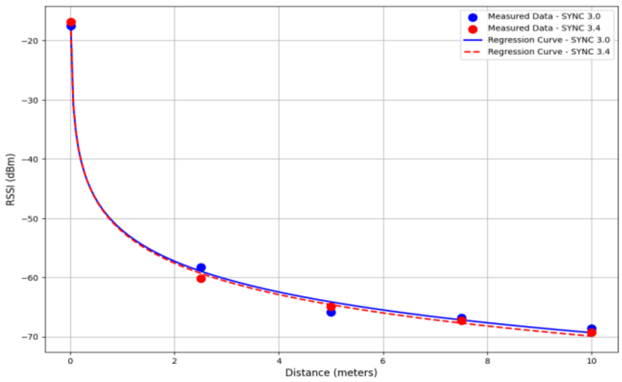
Data collected from two separate, but identical devices also showed equivalent results. This confirms the reliability measurement of the devices (Graphic 2).

Graphic 2. Comparison of Logarithmic Regressions for RSSI vs. Distance from device 1 and device 2



The data measured points for both SYNC 3.0 and SYNC 3.4 are nearly identical, indicating a highly comparable performance between the two systems. Although minor variations exist in the measured data at specific points, the overall signal behavior demonstrates that both SYNC versions exhibit predictable and consistent performance characteristics in a controlled environment.

Graphic 3. Comparison of Logarithmic Regressions for RSSI vs. Distance from SYNC 3.0 and SYNC 3.4



4. Conclusion

The reliability and validity of the experimental methodology were successfully confirmed through a systematic comparison of data. Measurements performed independently by two individuals, Person 1 and Person 2, yielded statistically equivalent results. Concurrently, data collected from two separate but identical devices, ESP32 rev.1 and ESP32 rev.3, were also found to be in strong agreement. Both SYNC 3.0 and SYNC 3.4 modules demonstrate predictable signal attenuation with increasing distance. Their overall performance in terms of average, maximum, and minimum signal strength is highly comparable, with only minor deviations observed at specific distances that can be explained by the process variation of the build of the components/boards.

This work can be used to create a model that will help define the design to meet the requirements and customers' expectations. An application for this work would be to identify any problem with the Bluetooth system of the infotainment ECU while it is not assembled in the vehicle making a replacement of a defective module cost less.

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