Implementation and Validation of the Optimized Space Diversified Antenna Arrays for Extended FM-RF Propagation

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ABSTRACT

FM broadcast antennas come in many shapes and sizes, but the dipole remains one of the most widely used designs because of its simple structure and reliable performance. For long-distance FM transmission, multiple antennas are often stacked to improve coverage and produce a stronger, more consistent radiation pattern. In these configurations, each antenna bay is adjusted to achieve the desired directional characteristics, and identical bays generate the same azimuth radiation pattern when installed as an array. The researchers designed and optimized a low-power FM broadcast antenna that performed better than the conventional design while meeting the required polarization and radiation pattern specifications based on antenna simulation results. However, because of the restrictions brought about by the COVID-19 pandemic, the antenna was never fabricated or tested using an antenna analyzer. As a result, its performance had only been evaluated through simulation. This study bridges that gap by fabricating the proposed antenna and validating its performance under actual operating conditions. The measured parameters obtained from an antenna analyzer were compared with the simulation results, including measurements taken after the antenna was mounted on a steel tower to determine the effects of the installation environment. The results showed close agreement between the simulated and measured values. The fabricated antenna produced a low reflection coefficient and a voltage standing wave ratio (VSWR) close to 1.0, indicating efficient power transfer and good impedance matching. Field measurements using the Deva Radio Explorer-Mobile FM Radio Analyzer also confirmed stronger signal performance than the conventional antenna. These findings demonstrate that the proposed design performs well not only in simulation but also in practical deployment, making it a viable option for low-power FM broadcasting.

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1. INTRODUCTION

FM broadcast antennas are available in many designs, but the dipole is still one of the most commonly used antennas for FM broadcasting. It is made up of two conductive elements that are typically half a wavelength long and are arranged horizontally or vertically. Dipole antennas are cheap, easy, and give out omni-directional coverage- they spread the signal in all directions. Yagi antennas are most commonly used for FM broadcasting, in cases where either targeted or extended coverage is desired. They are also called directional antennas or beam antennas. Yagi antennas have a set of parasitic elements arranged around the driven element to form a certain antenna pattern together. This will provide concentrated, directional coverage in one particular direction with gain and reach. One of the antennas commonly used for FM broadcast in the

Philippines and other countries is the shunt-fed slanted V dipole, a circularly polarized antenna with an omnidirectional pattern, invented by Peter K. Onnigian in 1970 and granted a United States patent.

Long-distance communication commonly uses an antenna configuration. An ideal setup is one that will allow the system to model properly a radio point source. To further boost performance, individual bays are fine-tuned for their directional capability; similar bays will replicate the identical azimuth radiation pattern when arranged in a stack. Challenges faced by the circularly polarized antenna design with an omnidirectional pattern have led to a shunt-fed circularly polarized FM broadcast antenna. The main challenge is to provide a higher gain for better signal penetration while maintaining a circular radiation pattern in the horizontal plane because of the alignment of its radiating elements.

In a previous study [1], a low-power FM broadcast antenna was designed and optimized using antenna simulation software. The results showed better performance than the conventional design while meeting the required polarization and radiation pattern specifications. However, the antenna was not fabricated or tested with an antenna analyzer because of the restrictions imposed during the COVID-19 pandemic. This study addresses that limitation by fabricating the proposed antenna and evaluating its actual performance. The measured parameters from the antenna analyzer are compared with the simulation results, including measurements taken after the antenna was installed on a steel tower to assess the effects of the mounting structure.

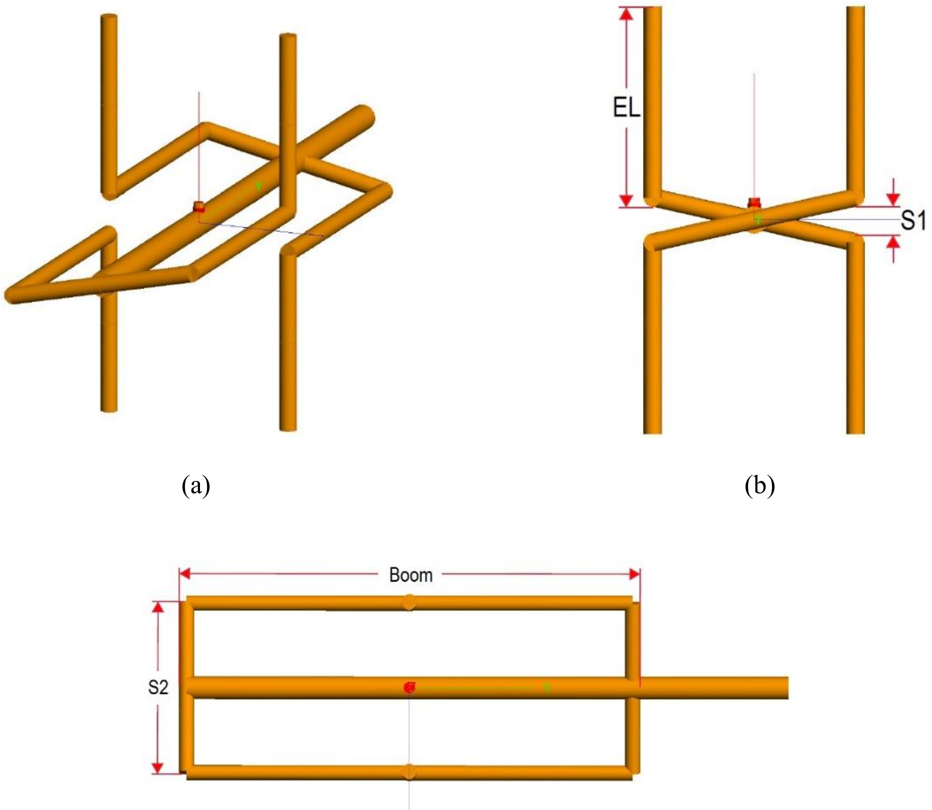
To meet the increasingly stringent criteria for long-distance communication in modern years of FM broadcasting, a high-gain antenna is in high demand. The dipole antenna used to broadcast the FM signal must radiate in every direction and be polarized so that all receivers can receive it. As it moves across space, an antenna produces an electromagnetic wave that varies with time. Assume that a wave moves outward over time, with the electric field constantly in a single plane. Because the deviation is up-and-down rather than side-to-side, the antenna is linearly polarized with vertical polarization. The antenna is considered to have elliptical polarization if the wave exhibits rotational motion, or spin, as it propagates through space. When an electromagnetic wave moves in a circular path, the antenna is said to have circular polarization. Circular polarization helps lessen the effect of the relative orientation between transmitting and receiving antennas [2]. CP antennas are widely used in radar, satellite communication, remote control systems, and mobile telecommunication systems because they can reduce multipath fading, perform well under adverse weather conditions, operate non-line-of-sight (NLOS), and are more mobile than linearly polarized antennas [3]. For a circularly polarized antenna, an axial-ratio beam width (ARBW) of 0 dB but not more than ±3dB is very important for signal coverage efficiency [4]. Circularly polarized (CP) antennas require a relatively large 3-dB axial ratio (AR) angular beamwidth to allow signal transmission and reception over a wide field of view [5].

The dipole antenna is the most powerful of all radio frequency antennas. It is often used by itself, but it can also be used as the driving element for many other RF antenna designs [6]. The performance of an individual dipole antenna element is usually not good enough for practical radio transmission and reception applications [7]. A single-element antenna is not a good choice for meeting technical requirements, especially for FM radio transmission, because its performance is poor. The electromagnetic field patterns in both the E and H planes of a singular antenna show a wide pattern; hence, its directivity is low [8]. Most applications need a high-directivity antenna to satisfy the requirement of long-distance communication. In present day communication systems, a variety of techniques are used to fulfill the requirement. It relies mainly on the practical design of antenna arrays to realize the propagation of signals of good quality and low interference in transmission [9]. An antenna array is a group of identical antenna elements that cooperate to behave as a single radiating element [7].

The latest advancements in wireless communication technologies have significantly increased the need for efficient antenna array systems [10]. Antenna arrays using multiple dipole antennas offer better performance than those using a single dipole. Antenna arrays are used to improve channel capacity and signal quality in wireless communications of today and the future [11]. The main factor in the design process of such an array is the selection of locations for the antennas within the array. Two dipoles are stacked vertically or bayed horizontally above each other. They are fed to emit radiation in-phase, which increases the directivity of the antenna. Stacking two dipoles enhances their directivity in the E-plane, whereas placing them side by side enhances their directivity in the H-plane [12]. Collinear antenna arrays are used to obtain enhanced antenna gains and are formed by the vertical alignment of similar bays [13]. Even though the grouping of multiple antennas might lead to higher costs and increased size, it also offers many significant advantages such as enhanced directivity, improved gain, wider bandwidth, and multi-functionality [14].

According to [15], the signal strength of the antenna was defined by the Federal Communications Commission (FCC) for the subsequent thresholds of minimally acceptable signal strength designated for the coverage zones, as adopted in the study by [16], as shown in Table 1-1. The FCC outlines two distinct levels of signal contours for various applications. The initial level corresponds to the 70 dBu contour (3.16 mV/m), which is essential for covering the primary community of interest for the license. The subsequent level corresponds to the 60 dBu contour (1 mV/m), which defines the main service area.

The optimized FM antenna design was extracted from a previous study [1] using Feko, a powerful computational electromagnetics (CEM) software developed by Altair Engineering, for the simulation and analysis of electromagnetic issues for 3D objects of any shape. Figure 1-1 shows the optimized FM antenna design to be implemented in this study, consisting of two vertical dipoles with a rectangular loop placed back-to-back on a boom to form an antenna array.



(a) (b)

(c)

Figure 1-1. Design of the optimized FM antenna (a) Isometric View, (b) End View, and (c) Top View

Table 1-1. Minimum Signal Strength for each Service Area

Dimension/ Physical Specification	Value
Element Length	0.088λ
Dipole Vertical Spacing (S1)	0.021λ
Dipole Horizontal Relative Spacing (S2)	0.093λ
Boom Length	0.244λ

Table 1-2. Physical dimensions of the optimized FM antenna.

Service Area	Minimum Signal Strength	
	mV	dBu
Rural Areas	0.05	34
Suburban	1.00	60
Principal Community	3.16	70
Highest Usable level	12.64	82

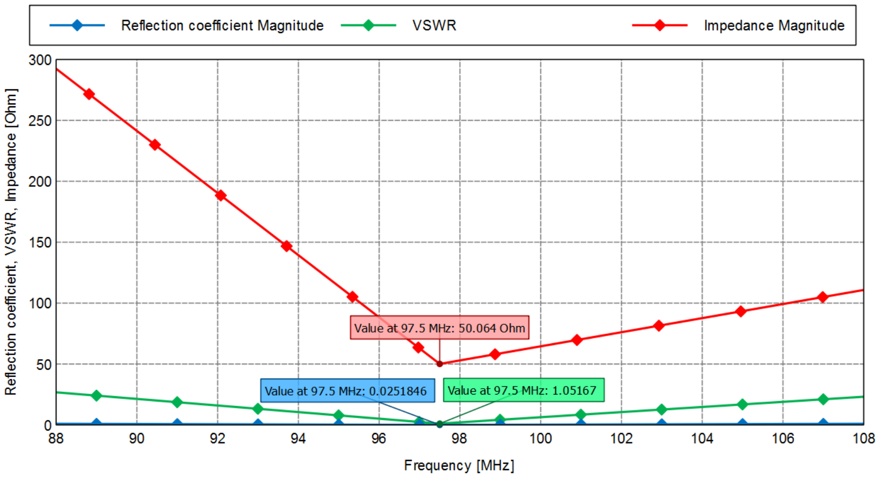


Figure 1-2. Cartesian graph showing the reflection coefficient, Voltage Standing Wave Ratio (VSWR), and impedance value of the optimized Frequency Modulation (FM) antenna tuned at 97.5 MHz

The specifications of the proposed antenna design, exported from the simulation software, are shown in Table 1-2. Figure 1-2 illustrates the graphs of the reflection coefficient, Voltage Standing Wave Ratio (VSWR), and impedance of the optimized FM antenna, yielding promising results that demonstrate its usability and suitability for practical applications, given its compliance with the characteristics.

The antenna's form factor, the antenna's interaction with its surroundings, such as the packaging in which the antenna is housed, and the antenna's contact with the human body and other nearby objects are all variables that must be thoroughly considered in the design. Most FM antennas are attached to the side of a metallic tower or pole and can provide acceptable omnidirectional azimuth patterns [17]. This study aims to validate the proposed antenna by comparing the simulation results with antenna analyzer measurements, including those obtained after the antenna was mounted on a steel tower.

2. RESEARCH METHOD

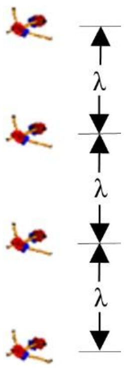


Figure 2-1. The collinear array for the application, formed by four bays on the vertical plane, adapted from [17].

The antenna design specifications and parameters were exported from the antenna simulation software called Feko. This included information such as the antenna's dimensions, material properties, and feeding mechanism. The complexity of the antenna design, the materials used, and the available resources dictate the method of fabrication. Manual fabrication involves the use of metals, such as copper and brass. Cutting or etching the conductive material, forming or bending wires, soldering components, and assembling the different parts are some of the processes involved in fabrication. During the fabrication process, the dimensions, alignments, and connections of the fabricated parts were checked and verified to ensure that they met the design specifications. The evaluation of the fabricated antenna comes immediately after completing the fabrication process. The antenna is connected to measuring equipment, such as an antenna analyzer or a network analyzer, and fine-tuning and measurements are carried out to validate its performance. The measured results and the simulated data used to assess fabrication accuracy were compared. For practical applications, the following antenna characteristics should be considered: reflection coefficient, voltage standing wave ratio (VSWR), RF field strength, and impedance, as shown in Table 2-1. This study uses a 4-bay collinear array to illustrate the antenna's RF field strength, as shown in Figure 2-1. It employs the shunt-fed, slanted V dipole along with the proposed FM antenna for both implementation and validation, details of which have been provided earlier. The four bays that constitute the collinear array are arranged one wavelength apart. This configuration is commonly adopted for practical applications, and it is used to achieve the requisite gain, particularly in regional FM broadcasting stations.

Table 2-1. Validation of the applicability of the characteristics of the optimized FM Antenna for implementation.

Antenna Characteristics	Parameter	Acceptability
S-Parameter(S11)	Reflectionco efficient/ VSWR	r=closed to 0 close to unity
Impedance	Frequency defined	close to 50 ohms
RF Field Strength	(dBµV/m)	≥/20dBu in the far field

To enhance the analysis of the RF field strength, the antennas are affixed to the side of a metal tower, which helps mitigate potential pattern distortion caused by nearby objects. This is because the study uses a Deva Radio Explorer to measure RF field strength. All the elements in the array are tuned to operate at 98.1MHz, which is the authorized frequency used by the FM radio broadcasting entity associated with Cebu Technological University-Tuburan Campus, the home of the respondents. A survey/ campaign was conducted to assess the existing antenna system, a 4-bay slanted dipole, versus the proposed 4-bay antenna design for implementation and validation using DEVA Radio Explorer. The survey/campaign was undertaken to determine the radio signal coverage of two antennas mounted on a 210-foot tower using the DEVA Radio Explorer. The survey focused on the northern and western parts of Cebu to measure and compare the signal reach of the existing antenna with that of the proposed antenna, as shown in Figure 2-2. The colors and signal levels indicate the strength of the FM broadcast in different areas, as shown in Table 2-2.

Table 2-2. Validation of the signal strength thresholds for FM reception.

RF Level Range (dBµV)	Color Code	Reception Quality
0-19	Red to Brown	Very weak or no reception. Audio is noisy, unstable, or lost completely.
20-49	Light Green to Green	Usable reception, but quality varies. Lower range: Unstable stereo; Upper range: Stereo + RDS generally works.
50-69	Cyan to Light Blue	Good reception. Clean stereo, RDS decoding reliable.
70-90+	Dark Blue	Very strong reception. Excellent audio, with no dropouts; usually near the transmitter or in clear line-of-sight.

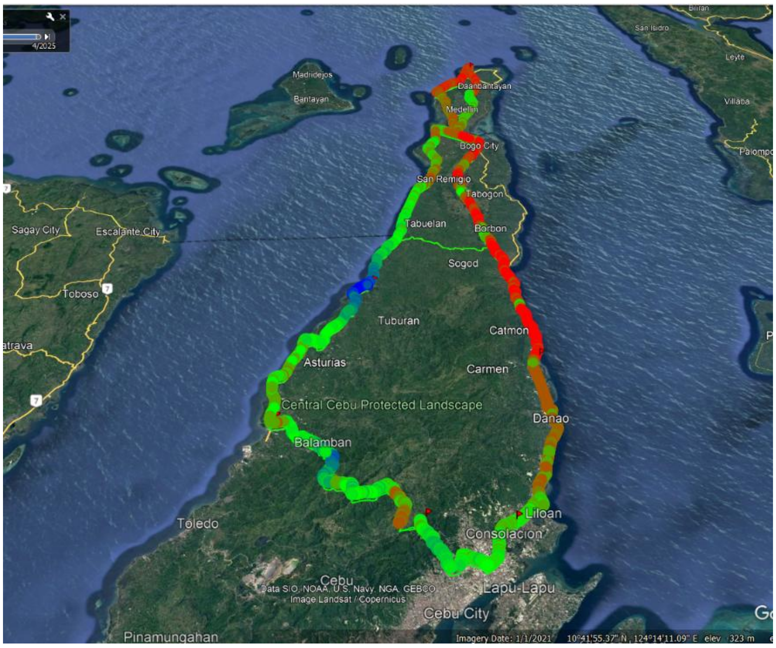


Figure 2-2. Shows the area reached by the station in the northern and western part of Cebu, exported from Google Earth via DEVA Radio Explorer equipped with Global Positioning System (GPS)

On Table 2-2, the scale indicates that weak signals (red to brown) often result in noisy or unstable reception. In contrast, medium signals (green) provide listenable quality but may still cut in and out. Stronger signals (cyan–blue) provide clear stereo sound and reliable station information (RDS). Stronger signals (cyan–blue) provide clear stereo sound and reliable station information (RDS). The darkest shade of blue stands for the best levels, where you should have very good, uninterrupted reception, usually close to the transmitter or in places with a clear path for the signal. The results obtained from the antenna analyzer and survey were used for validation and implementation to ensure that the proposed antenna system could indeed improve broadcast coverage and reliability. The data was collected by the proponents and analyzed using the cumulative distribution function.

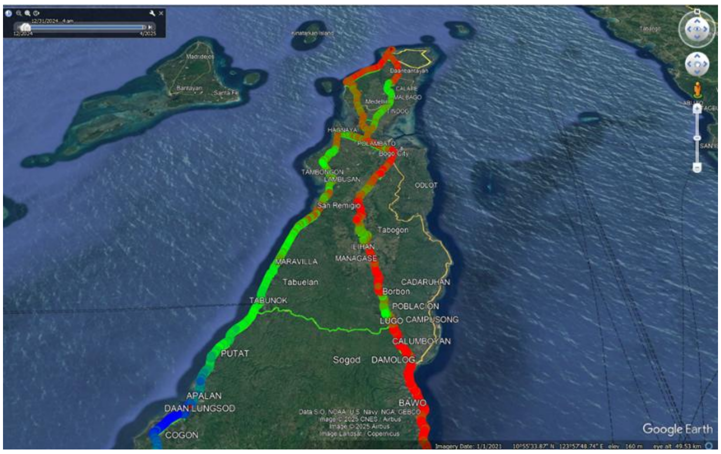
3. RESULTS AND DISCUSSION

This part of the paper shows pictures that prove the results of the proposed antenna design after making it and during the survey/campaign to measure the RF field strength of the existing slanted V antenna mounted on the FM station tower at Cebu Technological University-Tuburan Campus. Figure 3-1 shows the reading from an antenna analyzer, putting more focus on the obtained Impedance and VSWR values of the FM antenna tuned to 98.1 MHz as a single bay. The input impedance reading is 50.7 ohms; therefore, the reflection coefficient should be minimal, resulting in a VSWR of 1.01. The proposed FM antenna shows promising results, demonstrating its usability and design effectiveness, meeting the required characteristics for practical applications.

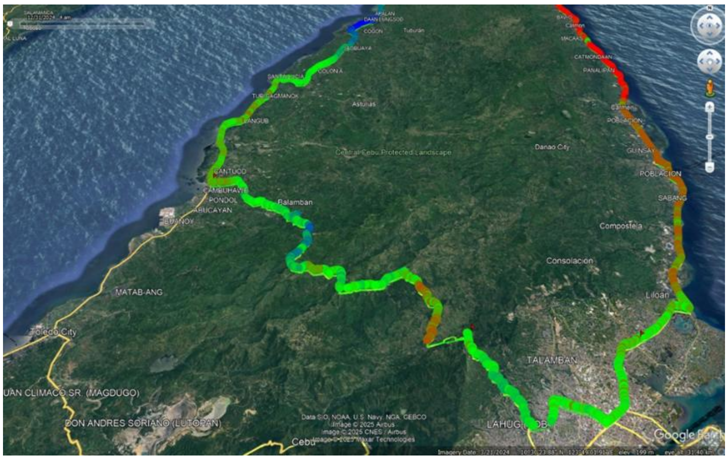
(a) (b)

Figure 3-1. The proposed FM antenna showing for (a) an individual bay tuned to 98.1FM, and (b) the antenna analyzer (RigExpert)

Figure 3-2 depicts the results of the survey/ campaign for the FM radio station RF field strength in the northern and western parts of Cebu, utilizing the existing slanted V dipole antenna in a collinear array. The corridor of the west coast (Tuburan → Tabuelan → San Remigio) appears mainly green with some blue spots, which means that the signal strength is uniformly strong. This can be attributed to the advantage of the over-water path and the lesser number of terrain obstructions from the transmitter's location. The northbound interior spine (up to the Medellin/Bogo junctions) exhibits a combination of green and yellow, indicating usable but varying strength as it goes behind hills/ridges. From Bogo to Medellin to Daanbantayan on the east coast, there are long stretches of orange/red due to shadowing from ridges in Cebu's central highlands and greater path length; hence, weaker signals. Around Daanbantayan's northern tip, the colors clump as red/orange—so this is behavior at maximum distance, with terrain and coastal bends cutting into line of sight. The islands offshore (the Bantayan area is visible on the map, but it wasn't sampled): Not measured here, but when the paths are mostly over water, expect reception to spike locally then die out quickly as a result of curvature/obstructions.



(a)



(b)

Figure 3-2. The range reached by the FM station in the (a) northern part of Cebu, and (b) western part of Cebu, using the existing antenna, the slanted V dipole in a collinear array.

To provide a reference view of the RF field strength shown in Figure 3-2, Figure 3-3 presents the color scaling, along with corresponding numerical values, in tabular form as previously mentioned.

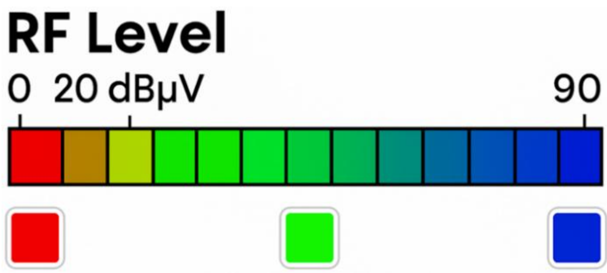


Figure 3-3. The RF level scale used in Deva Radio Explorer to measure RF field strength

Table 3-1. Summary Statistics (RF Level, dBμV) of the existing slanted V antenna.

Metric	Value (dBμV)
Samples	2970
Mean	24.16
Standard Deviation	16.91
Minimum	4.50
25th Percentile	12.10
Median (50th)	19.60
75th Percentile	29.30
Maximum	91.40

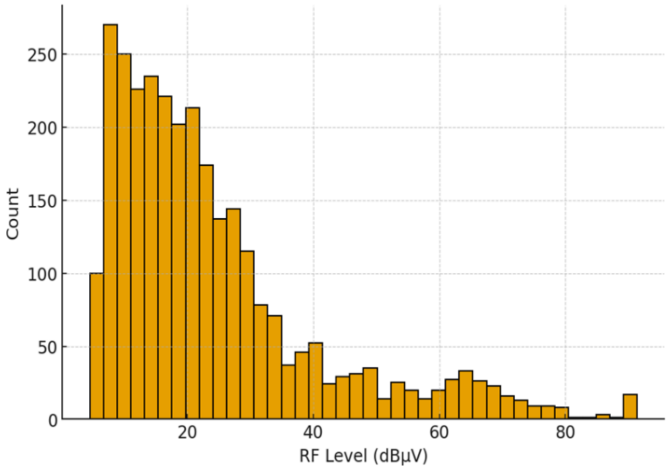


Figure 3-4. Distribution of FM signal strength (RF Level dBuV) of the existing slanted V antenna.

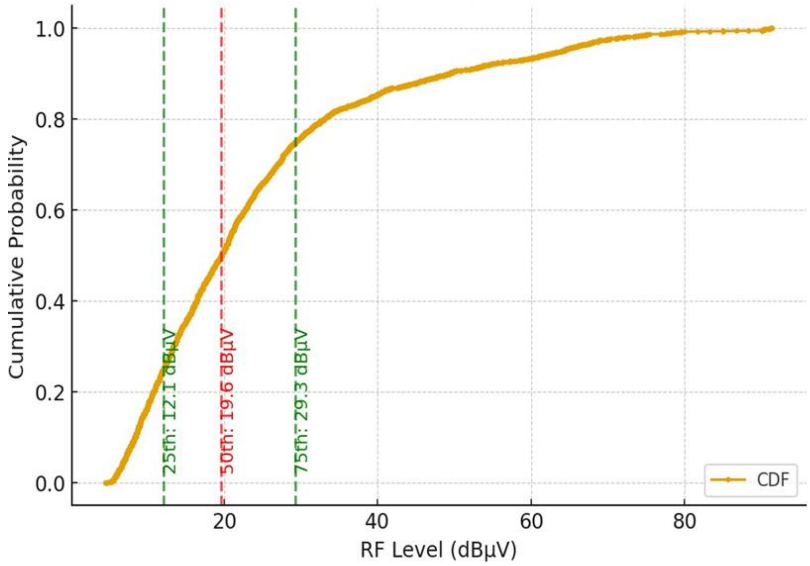
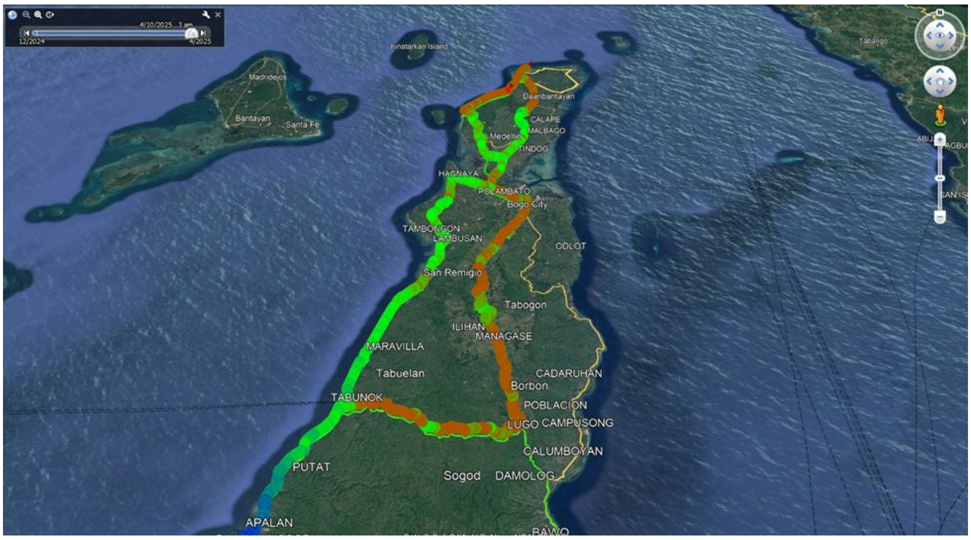


Figure 3-5. Cumulative Distribution Function (CDF) of the FM signal strength of the slanted V antenna

The FM signal survey reveals the following essential findings: Most measurements range from 10 to 30 dBµV, signifying standard usable reception levels. The median RF Level is roughly 19.6 dBµV, indicating that half of all survey measurements are below this threshold. The 75th percentile is at 29.3 dBµV, which means better reception areas. A few readings go over 70 to 90 dBµV, which relates to very high-quality reception areas. Below 10 dBµV, values indicate poor to marginal coverage, with probably inconsistent reception. The histogram shows the distribution of signal strengths. The CDF shows cumulative probabilities at percentiles.

This section of the paper provides visuals demonstrating the results of the survey/campaign on the RF field strength of the proposed FM antenna for implementation and validation, positioned atop the radio transmission tower of Cebu Technological University-Tuburan Campus.

Figure 3-6 shows the northern and western parts of Cebu during the survey/campaign of the FM radio station's RF field strength, with the proposed FM antenna in a collinear array for implementation and validation. The western coastal route (Tuburan Proper → Putat → Apalan) showcases numerous green and cyan markers, with occasional blue spots — signifying unimpeded signal propagation over water and along the coastline, along with fewer obstacles in the terrain. Mobile and indoor reception is likely to be dependable in this area. The interior/central spine shows a color change from mix green to orange. As the measurement points move across valleys or behind ridgelines, the landscape of hills and ridges in the Central Cebu Protected Landscape cast shadows and create signal degradation. The northeastern route and the northern tip (Bogo/Medellin/Daanbantayan) have large segments of orange and red, especially near the extreme north region, which means that the signal of the station almost reaches or exceeds its reliable service limit in this area, due to distance and ridge interference. Zones of abrupt change from green to orange or red over short distances probably indicate quick terrain blockages like ridges or local multipath, clutter, or interference. In simpler terms, it means that people on the western coast get a good signal while those in the northeast and far north experience bad reception and signal cut off most of the time.



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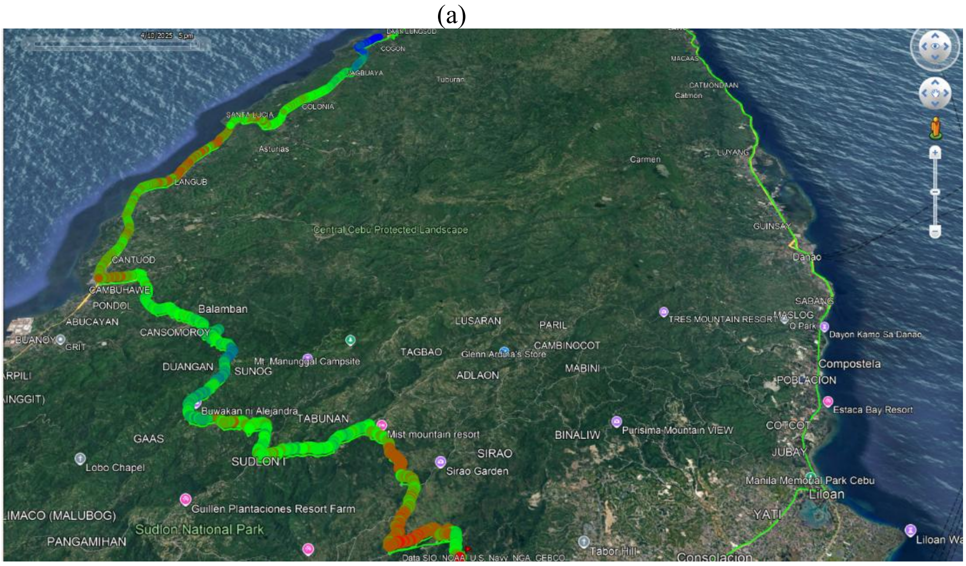

(b)

Figure 3-6. The range reached by the FM station in the (a) northern part of Cebu, and (b) western part of Cebu, using the proposed FM antenna in a collinear array for implementation and validation.

Table 3-2. Summary Statistics (RF Level, dBμV) of the proposed FM antenna.

Metric	Value (dBμV)
Samples	5950.00
Mean	28.10
Standard Deviation	17.55
Minimum	7.20
25th Percentile	15.70
Median (50th)	22.70
75th Percentile	34.30
Maximum	91.70

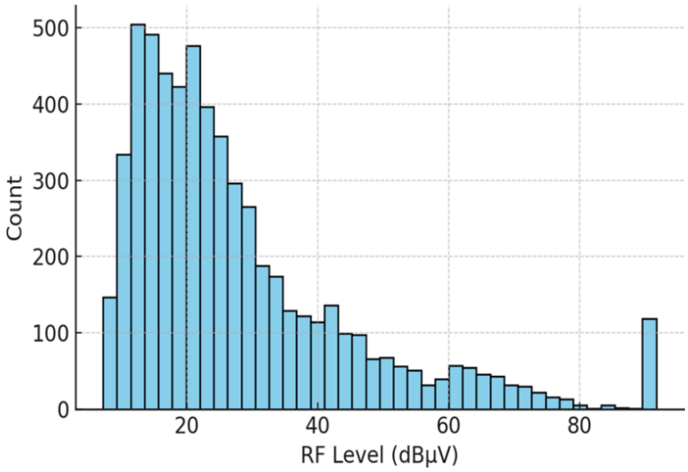

Figure 3-7. Distribution of FM signal strength (RF Level dBuV) of the proposed FM antenna.

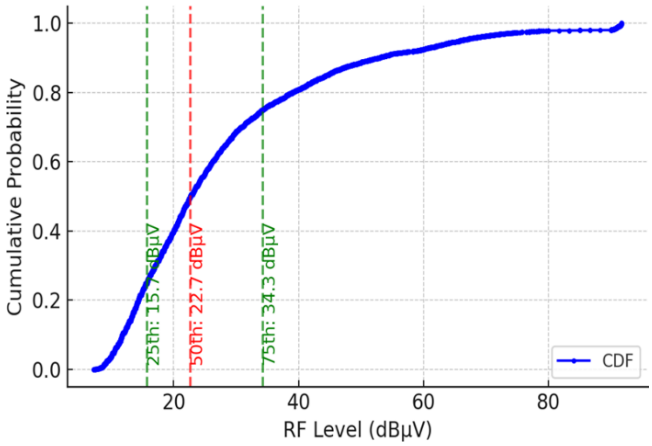

Figure 3-8. Cumulative Distribution Function (CDF) of the FM signal strength of the proposed FM antenna

The analysis shows that most signal levels fall between 15 and 35 dBμV, which is usable FM reception. Table 3-2 gives the 25th percentile at around 15.7 dBμV, the median at 22.7 dBμV, and the 75th percentile at 34.3 dBμV. Only a small fraction of measurements exceeded 60 dBμV — very strong reception zones. The histogram in Figure 3-7 illustrates the distribution of signal strengths; the CDF in Figure 3-8 highlights cumulative probabilities, marked by percentiles.

4. CONCLUSION

Results of implementation and validation of the optimized space-diversified antenna arrays prove the proposed FM antenna design to be better than the existing slanted V dipole system. Reading on the antenna analyzer showed VSWR close to unity and impedance close to 50 ohms, which means there would be very low reflection losses and that it is well matched to broadcasting equipment. Field measurements using the DEVA Radio Explorer showed very good improvement in average RF field strength with higher median and 75th percentile values compared to the existing antenna.

The proposed antenna offered much greater and more reliable coverage along the entire length of the western coastal corridor, with constant strong reception and few dropouts. Terrain and ridge obstructions still posed problems in the northern and northeastern routes regarding the coverage. The optimized antenna showed better gains in usable reception levels over most areas studied. In the end, it was proven that the optimized antenna design does not only meet the required technical standards for FM broadcasting but enhances the station's signal reach and reliability. This, therefore, confirms its applicability for practical deployment in FM broadcasting, supporting improved service to a wider listening community.

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BIOGRAPHY OF AUTHORS

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