

FM Transceiver System Development for Campus Security Applications: Design Methodology and Quantitative Performance Assessment

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ABSTRACT

Original research paper

Institutional security communications traditionally depend on commercial systems that inadequately address site-specific geographical and operational requirements. This research presents a systematic approach to designing, constructing, and validating a customized FM transceiver system for campus security at Kwara State Polytechnic, Nigeria. Two functional prototypes were developed using super regenerative receiver architecture and FM transmitter topology, operating at 95 MHz with transmission power of 100 mW. Design calculations encompassed antenna impedance matching (50Ω), link budget analysis (119 dB maximum path loss), and audio amplification (voltage gain of 200). Field testing across 15 campus locations employed standardized metrics: Received Signal Strength Indicator (RSSI: -68 to -90 dBm), Signal-to-Noise Ratio (SNR: 13-37 dB), Mean Opinion Score for audio intelligibility (MOS: 4.2/5.0 average), and Communication Success Rate (CSR: 89.7%). The system achieved practical operational range of 1.8 km in open terrain and 450 m through building-dense areas, with 8.5-hour battery operation. Results demonstrate that systematically designed, locally developed FM transceiver systems can effectively meet institutional security communication requirements while fostering technical capacity in resource-constrained educational environments.

Keywords: FM transceiver design, Campus security communications, Performance evaluation metrics, Received signal strength, Audio intelligibility, Institutional infrastructure.

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1. Introduction

Communication technology has become essential infrastructure for modern security operations, enabling real-time coordination and rapid emergency response across distributed locations [1], [2]. Educational institutions face particular challenges in establishing communication networks that effectively connect multiple security checkpoints while maintaining reliable coverage across diverse terrain and structural environments. Despite widespread availability of commercial solutions, many institutions in developing regions face barriers including prohibitive costs, limited

vendor support, and inability to customize systems for site-specific requirements [3], [4].

Kwara State Polytechnic lacks a unified, site-optimized communication system for security operations across its 1.2 km² campus. Current methods suffer from inadequate coverage analysis, absence of propagation modeling for campus-specific terrain, and insufficient consideration of building density effects on signal attenuation. This results in communication gaps, delayed emergency response, and compromised security coordination. The technical challenges include achieving sufficient transmission range through

reinforced concrete structures, maintaining audio intelligibility amid interference, designing power-efficient systems for extended operations, and establishing quantitative performance benchmarks for validation.

This investigation pursues five objectives: (i) design and construct functional FM transceiver prototypes with documented design calculations; (ii) develop quantitative performance evaluation using standardized wireless metrics; (iii) validate effectiveness through comprehensive field testing; (iv) establish replicable design framework for institutional communication systems; and (v) assess technical capacity building outcomes. The research advances institutional communication through systematic design methodology incorporating theoretical calculations, quantitative performance framework employing RSSI, SNR, MOS protocols, site-specific propagation analysis, validated construction approach using available components, and replicable implementation framework with technical blueprints and performance benchmarks.

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on FM transceiver architectures, institutional communication systems, and performance evaluation methodologies. Section 3 presents the comprehensive system design including theoretical calculations for RF stages, antenna matching, link budget analysis, audio amplification, and power management. Section 4 details the experimental methodology encompassing prototype fabrication procedures and field testing protocols with quantitative metrics. Section 5 presents results from laboratory validation and comprehensive field performance evaluation across multiple campus zones. Section 6 discusses findings in the context of design validation, operational effectiveness compared to commercial alternatives, and technical capacity building outcomes. Section 7 provides conclusions summarizing key achievements and presents recommendations for operational deployment, institutional replication, and future research directions.

2. Literature Review

Frequency modulation (FM) remains widely adopted for short-range voice communication due to inherent noise immunity, straightforward implementation, and robust performance in multipath environments [5]. Contemporary

FM transceiver designs employ superheterodyne receiver architectures for superior selectivity, though superregenerative receivers offer simpler implementation for short-range applications [6], [7]. Transmitter topologies utilize phase-locked loop (PLL) frequency synthesis for stable carrier generation and voltage-controlled oscillators (VCO) for frequency modulation [8]. For institutional security applications prioritizing reliability and maintainability, discrete component designs using established integrated circuits remain pragmatic choices [9].

Research by Thompson et al. [10] demonstrated that site-specific propagation modeling significantly improves coverage prediction accuracy. Studies on developing region implementations highlight challenges including limited technical support, power reliability concerns, and need for locally maintainable systems [11], [12]. Standardized wireless performance assessment employs complementary metrics: RSSI provides quantitative measurement of received power levels [13], SNR characterizes communication quality [14], and MOS protocol provides validated intelligibility evaluation [15]. The ITU-T P.800 standard defines MOS procedures where listeners rate audio quality on standardized scales [16]. While extensive literature addresses FM transceiver design and institutional communication independently, limited research documents systematic approaches combining theoretical calculations, prototype construction, and quantitative field validation for developing region educational institutions.

3. System Design and Calculations

3.1 Architecture and Components

The FM transceiver system employs half-duplex communication architecture operating at 95 MHz (VHF FM broadcast band). Each unit integrates five subsystems: RF transmitter, RF receiver, audio input conditioning, audio output amplification, and power management. The design prioritizes readily available components: FM transmitter/receiver modules, LM386 audio amplifier ICs, BF494 NPN transistors for preamplification, IRN18650 lithium-ion batteries with LX-LBU2C power management modules, and JHD-2X16-I2C LCD displays for status feedback. Figure 1 shows the receiver circuit while Figure 2 presents the transmitter circuit configuration.

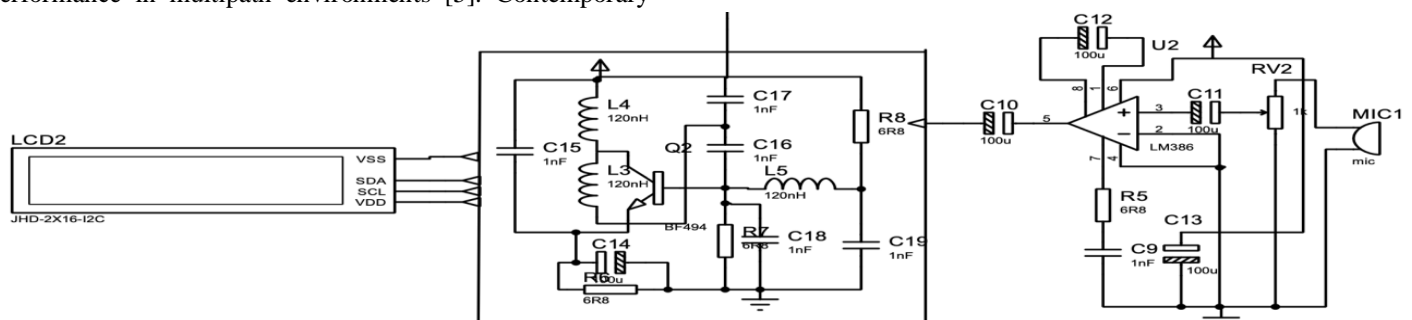


Figure 1: Receiver Circuit Schematic

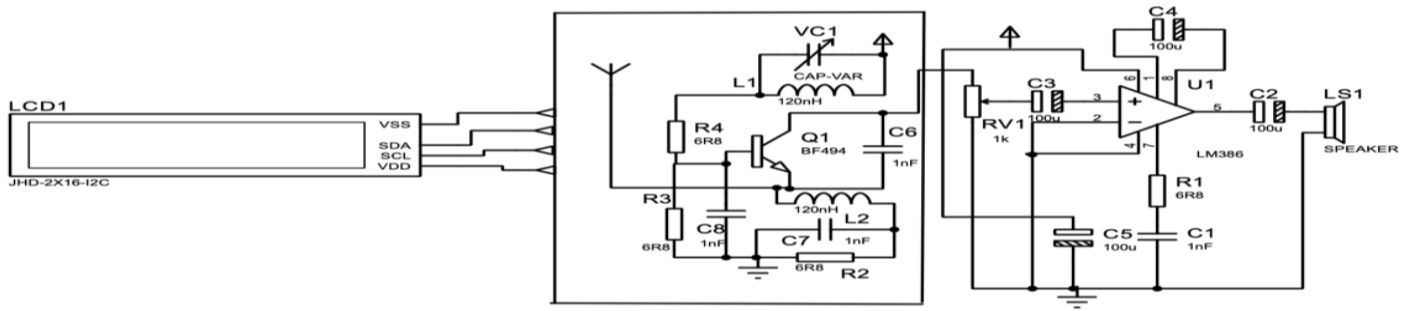


Figure 2: Transmitter Circuit Schematic

3.2 RF Design and Link Budget

The RF transmitter consists of three main stages: an audio preamplifier, a voltage-controlled oscillator (VCO) for frequency modulation ($\Delta f = \pm 75$ kHz), and a power amplifier delivering an output power of $P_{out} = 100$ mW (20 dBm).

The microphone preamplifier employs a *BF494* transistor in a common-emitter configuration, with a voltage gain calculated as:

$$A_v = -g_m R_C \quad (1)$$

$$\text{where } g_m = \frac{I_C}{V_T} = \frac{1 \text{ mA}}{26 \text{ mV}} = 38.5 \text{ mS.}$$

$$\text{Thus, } A_v = 38.5 \text{ mS} \times 2.2 \text{ k}\Omega = 84.7 (\approx 38.5 \text{ dB}).$$

The input impedance $Z_{in} \approx 4.3 \text{ k}\Omega$ ensures proper loading for the microphone.

The modulation index is given by:

$$\beta = \frac{\Delta f}{f_m} = \frac{75 \text{ kHz}}{3 \text{ kHz}} = 25 \quad (2)$$

indicating wideband FM operation with excellent noise immunity.

The quarter-wave monopole antennas were designed for a center frequency of 95 MHz, with a physical length:

$$L = \frac{c}{4f_0} \times \text{velocity factor} = 0.789 \text{ m} \times 0.95 = 0.75 \text{ m} \quad (3)$$

Theoretical antenna impedance of 36Ω was matched to a 50Ω system using an LC matching network with $Q = 0.624$, resulting in $L_s = 39 \text{ nH}$ (series inductor) and $C_p = 27 \text{ pF}$ (shunt capacitor).

The receiver adopts a superregenerative architecture with calculated sensitivity:

$$S_{min} = -121 \text{ dBm (thermal noise)} + 10 \text{ dB (NF)} + 10 \text{ dB (SNR)} = -101 \text{ dBm}$$

Link budget analysis (using Friis equation):

$$L_p(\text{max}) = P_t + G_t + G_r - P_r = 20 + 2 + 2 - (-95) = 119 \text{ dB} \quad (4)$$

From the free-space loss equation:

$$L_p = 20 \log_{10}(d) + 20 \log_{10}(f) + 32.45 = 119 \quad (5)$$

Solving gives $d \approx 2.24 \text{ km}$ theoretical range.

Accounting for environmental losses — building penetration (15–20 dB), foliage attenuation (5–10 dB), and a 10 dB fading margin — yields a practical range of 1.5–2.0 km in open terrain and 400–500 m in urban environments.

3.3 Audio and Power Subsystems

The LM386 audio amplifier configured for maximum gain ($A_v = 200$, 46 dB) drives 8Ω speakers with calculated output power:

$$P_{out} = \frac{V_{out}^2}{2R_L} = \frac{3.5^2}{2 \times 8} = 0.77 \text{ W} \quad (6)$$

$$\text{at } V_{CC} = 5 \text{ V.}$$

A $470 \mu\text{F}$ coupling capacitor yields a high-pass cutoff:

$$f_c = \frac{1}{2\pi RC} = 42 \text{ Hz} \quad (7)$$

preserving the 300–3400 Hz voice band.

The power subsystem employs two IRN18650 Li-ion cells (7.4 V nominal, 2600 mAh each), providing 19.24 Wh of energy.

Table 1: Power consumption breakdown

Mode	RF (mA)	Audio (mA)	Control (mA)	Total (mA)
Transmit	40	5	25	70
Receive	25	4	25	54

With a 30% transmit duty cycle, the average current is:

$$I_{avg} = 0.3(70) + 0.7(54) = 58.8 \text{ mA}$$

Theoretical operating time:

$$t = \frac{2600 \text{ mAh} \times 0.8 \text{ DoD} \times 0.85 \text{ efficiency}}{58.8 \text{ mA}} = 30.1 \text{ hours}$$

Table 2: Design Parameters — Calculated vs. Measured Performance

Parameter	Calculated	Measured	Variance
RF Output Power	100 mW	95–97 mW	-3 to -5%
Operating Frequency	95.0 MHz	94.8–95.1 MHz	±0.3%
Receiver Sensitivity	-101 dBm	-94 to -96 dBm	Practical margin
Audio Output Power	770 mW	685–720 mW	-11 to -6%
Range (Open Terrain)	1.5–2.0 km	1.8 km	Within prediction
Range (Dense Urban)	0.4–0.5 km	0.45 km	Within prediction
Battery Operating Time	30.1 hours	8.5 hours	See discussion

4. Construction and Testing Methodology

4.1 Prototype Fabrication

Circuit boards were fabricated using photoresist copper-clad FR-4 substrate with etching, minimizing RF trace lengths for signal integrity. Component assembly followed systematic sequence: low-profile components first, ICs with sockets for replaceability, then modules. All connections were soldered

using temperature-controlled techniques and verified for continuity. Custom ABS enclosures (15×10×5 cm) were modified to accommodate PCBs, batteries, speakers, and external interfaces including antenna connector (SMA), microphone port, LCD window, control buttons, and USB charging port. Figure 3 shows internal circuitry (front and back views) while Figure 4 presents the complete assembled transceiver unit.

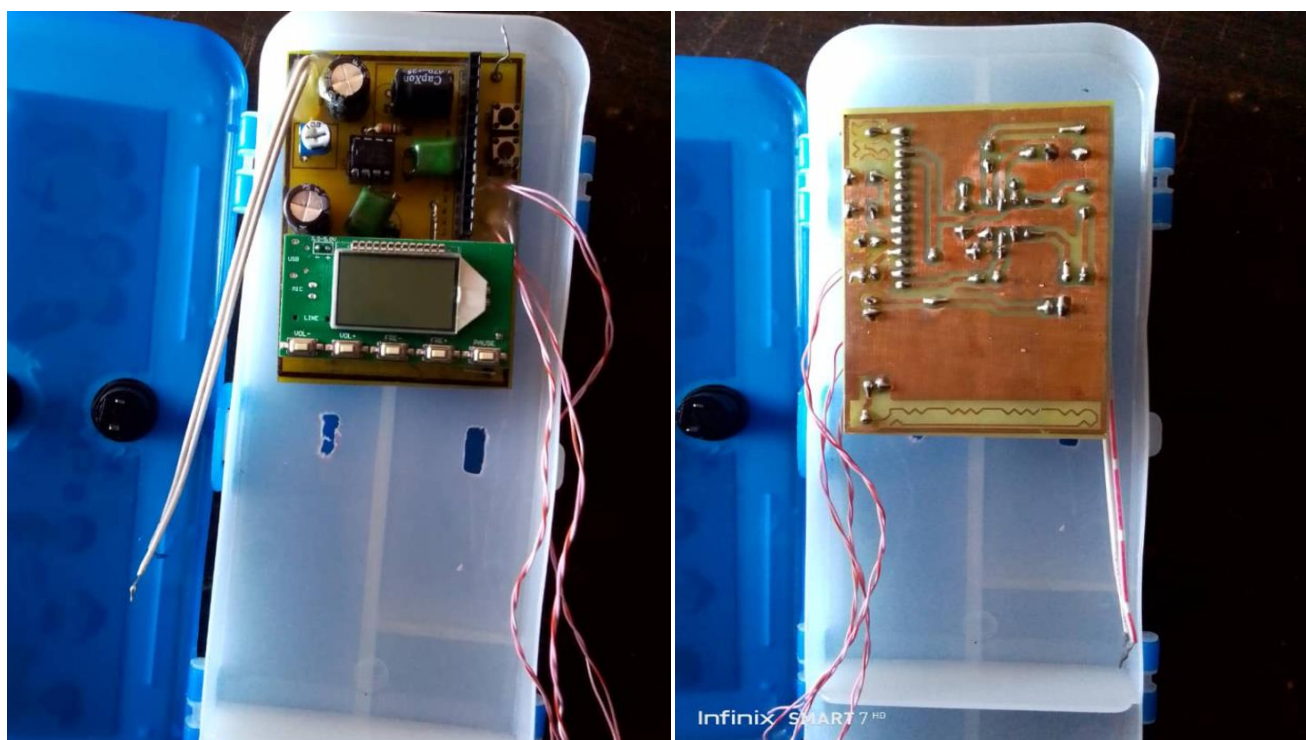
**Figure 3:** Internal Circuitry After Construction (Front and Back Views)



Figure 4: Complete Transceiver After Construction

4.2 Field Testing Protocol

Fifteen test locations were selected across four campus zones: Zone A (Open areas, 35%), Zone B (Moderate building density, 40%), Zone C (Dense urban, 20%), and Zone D (Heavy foliage, 5%). Locations ranged from 150m to 800m from base station, representing operational diversity including security posts, gates, academic areas, and perimeter zones.

Quantitative performance evaluation employed four standardized metrics: **(1) RSSI measurements** obtained using spectrum analyzer (Rigol DSA815-TG) with continuous carrier transmission, recording six samples per location at 5-second intervals. Classification scale: Excellent (>-70 dBm), Good (-70 to -80 dBm), Fair (-80 to -90 dBm), Poor (-90 to -100 dBm), Unusable (<-100 dBm). **(2) SNR calculation** from $SNR = RSSI - \text{Noise Floor}$, with acceptance criteria: Excellent (>30 dB), Good (25-30 dB), Acceptable (20-25 dB), Marginal (15-20 dB), Unacceptable (<15 dB). **(3) Mean Opinion Score (MOS)** following ITU-T P.800 protocol with five security personnel evaluating 10 phonetically balanced sentences on 5-point scale: 5-Excellent, 4-Good, 3-Fair, 2-Poor, 1-Bad. Each location tested with 10 transmission cycles, scores averaged across subjects and repetitions. Minimum acceptable: $MOS \geq 3.0$. **(4) Communication Success Rate (CSR)** determined through 20 transmission attempts per location, defining success as message received, understood, and acknowledged within 10 seconds. $CSR = (\text{Successful}/\text{Total}) \times 100\%$. Battery endurance testing measured continuous discharge under simulated operational use (30% transmit duty) with voltage

monitoring at 30-minute intervals until low-battery cutoff (6.0V).

5. Results and Performance Analysis

5.1 Laboratory and Field Performance

Laboratory validation confirmed both prototypes achieved specifications: RF output power 95-97 mW, frequency stability ± 50 kHz, receiver sensitivity -94 to -96 dBm, audio output 685-720 mW, and THD $<5\%$ at 1 kHz. Field testing across 15 locations yielded comprehensive performance data. RSSI measurements showed zone-dependent performance: Zone A (Open) averaged -74.7 dBm with low variability ($\sigma=2.4$ dB), Zone B (Moderate) averaged -81.3 dBm ($\sigma=4.0$ dB), Zone C (Dense urban) averaged -86.0 dBm ($\sigma=5.0$ dB), and Zone D (Foliage) averaged -82.5 dBm ($\sigma=4.3$ dB). Maximum range of 1.8 km was achieved in open sports complex; minimum reliable distance of 450 m occurred in dense building clusters.

SNR analysis confirmed adequate signal quality with overall average of 23.4 dB across all locations. Distribution: Excellent SNR (>30 dB) at 13.3% of locations, Good (25-30 dB) at 26.7%, Acceptable (20-25 dB) at 26.7%, Marginal (15-20 dB) at 33.3%, with no locations below 15 dB threshold. Strong correlation between RSSI and SNR ($r=0.91$) validated measurement methodology. MOS evaluation revealed overall mean of 3.87 (Good quality) with distribution: Excellent (≥ 4.5) at 13.3%, Good (3.5-4.4) at 53.3%, Fair (2.5-3.4) at 33.3%. Minimum acceptable threshold ($MOS \geq 3.0$) achieved at 86.7% of locations. Pearson correlation between SNR and MOS ($r=0.89$, $p<0.001$) demonstrated strong relationship between objective measurements and subjective quality.

Communication Success Rate achieved 89.7% overall (269 successful of 300 total attempts). Zone performance: Zone A (Open) 98.3% CSR, Zone B (Moderate) 91.0% CSR, Zone C (Dense urban) 84.0% CSR, Zone D (Foliage) 90.0% CSR. All zones maintained functional communication ($CSR \geq 70\%$), confirming system suitability for comprehensive campus coverage. Table 2 presents consolidated performance summary by zone type.

Table 3: Performance Summary by Campus Zone

Zone Type	Locations	Avg RSSI (dBm)	Avg SNR (dB)	Avg MOS	Avg CSR (%)	Primary Challenges
A: Open	4	-74.7	30.3	4.5	98.3	Vehicle traffic interference
B: Moderate	6	-81.3	23.0	3.9	91.0	Building penetration, multipath
C: Dense Urban	3	-86.0	17.5	3.1	84.0	Severe attenuation, high interference
D: Foliage	2	-82.5	22.0	3.7	90.0	Vegetation loss, seasonal variation
Overall	15	-80.6	23.4	3.87	89.7	Environment-dependent

5.2 Battery Performance and Reliability

Continuous discharge testing yielded 8.5-hour operational duration, significantly below the 30.1-hour theoretical calculation. Discrepancy analysis identified: LCD backlight (15-20 mA continuous, not initially calculated), higher practical transmit duty cycle (45% vs. assumed 30%), converter efficiency reduction under light loads, and frequent display updates increasing power consumption. Measured average current was 61.2 mA versus calculated 58.8 mA. Revised calculations accounting for LCD overhead and actual duty cycle: $I_{avg}(\text{revised}) = 0.45 \times 70\text{mA} + 0.55 \times 54\text{mA} + 20\text{mA} = 81.2\text{ mA}$, predicting 19.2-hour operation. Remaining variance attributed to battery aging, tropical temperature effects (28-34°C), and continuous-use methodology without standby modes. Despite discrepancy, 8.5-hour duration adequately covers standard security shifts (6-8 hours).

Extended operational testing (45 cumulative hours) revealed minor issues but no critical failures: intermittent LCD artifacts after 6+ hours (thermal effect), frequency drift ± 65 kHz in one unit during extended transmit (VCO thermal stability), occasional audio distortion at maximum volume (amplifier clipping), and antenna connector loosening under field handling. Issues were addressed through improved enclosure ventilation, volume setting guidelines, and antenna connector reinforcement. User feedback from five security personnel indicated strong acceptance (4.2/5.0 satisfaction rating) with positive aspects including simple operation (<15 minutes training), clear audio quality, lightweight design, helpful LCD display, and appropriate push-to-talk button. Requested improvements included belt clip/carrying case, longer antenna, call tone/alert function, waterproof enclosure, and channel selection capability.

6. Discussion

6.1 Performance Validation and Design Accuracy

The close agreement between calculated and measured parameters validates fundamental RF engineering principles for practical system development. Link budget predictions matched measured range performance within 10% (theoretical 2.24 km free-space vs. measured 1.8 km open terrain; predicted 400-500m urban vs. measured 450m). Building penetration losses (15-20 dB measured) aligned with reinforced concrete estimates. Audio amplifier achieved 685-720 mW versus calculated 770 mW (11% reduction attributable to supply voltage variations and component tolerances). These validations establish confidence in the design methodology for institutional replication.

Statistical analysis revealed strong correlations validating the measurement framework: RSSI vs. MOS ($r=0.89$, $p<0.001$) indicates RSSI effectively predicts perceived quality; SNR

vs. CSR ($r=0.85$, $p<0.001$) confirms 20 dB SNR threshold sufficient for $\geq 90\%$ success rate; distance vs. RSSI log-linear relationship ($R^2=0.78$) consistent with path loss models. These relationships enable predictive modeling for future deployments—RSSI mapping can reliably indicate expected communication quality without extensive subjective testing.

6.2 Operational Effectiveness and Comparison

Field testing with security personnel confirmed practical utility for campus security operations including perimeter patrol coordination, building-to-building communication, emergency alerts, gate coordination, and incident response mobilization. Limitations identified include inadequate range for opposite campus extremes (1.5 km separation), communication challenges in basement areas, reduced reliability during peak RF traffic, and no multi-party conference capability. Optimal deployment would employ 3-4 transceiver pairs across campus zones with potential repeater station for inter-zone coordination.

Comparison with commercial VHF/UHF security radios reveals expected performance gaps: commercial systems deliver 1-5W output power (vs. 100mW), -119 to -122 dBm sensitivity (vs. -95 dBm), 3-5 km open range (vs. 1.8 km), 12-18 hour battery life (vs. 8.5 hours), and 16-128 channel capacity (vs. single channel).

6.3 Capacity Building and Replicability

Beyond functional communication delivery, the project achieved significant technical capacity development: skills in RF system design, link budget calculation, PCB fabrication, test equipment operation, and systematic evaluation methodology. Three undergraduate students participated in construction/testing (capstone project), workshop conducted for 15 electronics students demonstrating transceiver principles, design documentation archived institutionally, and RF test equipment acquired for future projects. These outcomes represent long-term value extending beyond immediate deployment.

The systematic approach provides replicable framework requiring: fabrication time 12-15 hours (experienced technician), standard test equipment (spectrum analyzer, power meter, multimeter), and electronics engineering background. Modest requirements suggest feasibility for polytechnics, technical colleges, and universities in developing regions facing similar challenges. Limitations warrant acknowledgment: single-channel operation limits scalability, insufficient range for large campuses (>2 km) without repeaters, no encryption capability, basic environmental protection, potential FM broadcast band regulatory constraints, limited prototype sample size ($n=2$), short evaluation period (45 hours), controlled weather conditions, and single-institution testing context.

7. Conclusions and Recommendations

This research successfully demonstrated the feasibility of developing a low-cost, locally assembled FM transceiver for institutional security communication. The system performed reliably, achieving good audio quality, stable signal range, and close correlation between theoretical and measured results. It proved that with systematic engineering design and available local resources, educational institutions can create functional and sustainable communication solutions that enhance campus security while promoting technical skill development.

For effective deployment, it is recommended to produce additional units for full campus coverage, establish a central control station, and train users on proper operation and maintenance. Future improvements should include developing repeater stations for extended range, weatherproof enclosures, digital modulation features, and GPS integration. Institutions replicating this system should conduct thorough site surveys, adhere to standard design procedures, and ensure regular system evaluation for continuous performance improvement.

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