Faculty Mission: Enable 49 ML & AI Solutions

That 1.4 Billion People Are Waiting For

Where Intelligent Software Meets Designed-and-Built-in-India Hardware

Appendix D: Antenna Engineering

The Most Misunderstood Topic in Indian College IoT

D-1 Myths · D-2 Fundamentals · D-3 Link Budget · D-4 Selection · D-5 Multi-Wireless · D-6 Enclosure · D-7 NanoVNA · D-8 Vendors · D-9 App Notes

For: ECE & CSE Faculty · Students building any wireless IoT product · Anyone who has ever deployed LoRa and got 200m instead of 15km

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Why This Appendix Exists

> This appendix exists because of one conversation
> that happens in every college IoT lab in India:
>
> Student: 'Sir, I am using LoRa. I will get 15 km range.'
> Faculty: 'How did you calculate that?'
> Student: 'The datasheet says 15 km.'
> Faculty: 'What antenna did you use?'
> Student: 'The one that came with the module.'
> Faculty: 'Where did you place it?'
> Student: 'Inside the enclosure.'
> Faculty: 'What was your actual range?'
> Student: 'About 200 metres.'
>
> The 74-times difference between expected and actual range
> is an antenna engineering failure.
> Not a LoRa failure. Not a module failure. An engineering failure.
>
> This appendix closes that gap.

Section	Content
D-1	Antenna Myths vs Reality — The 7 Things Everyone Gets Wrong
D-2	Antenna Fundamentals — What Every IoT Engineer Must Know
D-3	Link Budget Calculation — LoRa 865 MHz India Step-by-Step
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D-1: Seven Antenna Myths — And the Engineering Reality Behind Each One

> Reality: 15 km is the theoretical free-space range under ideal conditions —
> flat terrain, elevated gateway, perfect antenna alignment, SF12, BW125, no interference.
>
> What you actually get in India:
>   Urban dense — concrete buildings: 200m–500m
>   Suburban — mixed buildings: 1–3 km
>   Open farmland — flat terrain: 5–10 km
>   Elevated gateway on tower: 8–15 km possible
>
> The datasheet number is a marketing number.
> The link budget calculation is the engineering number.
> Always calculate before you deploy.

> Reality: An antenna is a resonant structure. It is designed for a specific frequency.
> At other frequencies — radiation efficiency drops dramatically.
>
> Example: A 2.4 GHz WiFi antenna used at 865 MHz LoRa:
>   Physical length: 865 MHz antenna = 8.6 cm quarter wave
>   2.4 GHz antenna = 3.1 cm quarter wave
>   Using wrong antenna: return loss < 3 dB — 50% of power reflected back
>   Range: 15% of correct antenna
>
> Always match antenna to operating frequency.
> Measure with NanoVNA to verify.

> Reality: Gain pattern matters more than size.
> A directional antenna pointing in the wrong direction
> delivers less signal than a smaller omnidirectional antenna.
>
> A high-gain antenna concentrates signal in one plane.
> It reduces signal in other directions.
>
> For a sensor node with unknown orientation:
>   Omnidirectional (0–3 dBi) is correct.
>   Directional (6–12 dBi) is only correct if you know the direction.
>
> Match antenna pattern to your deployment geometry.
> Not to your range ambition.

> Reality: The module's PCB trace antenna was designed and characterised
> for the module in isolation — on a specific ground plane size.
>
> When you mount the module on your carrier board:
>   Your carrier board ground plane changes the antenna's resonant frequency
>   Your carrier board copper pours detune the antenna
>   Components near the antenna absorb RF energy
>   Your enclosure shifts the resonant frequency
>
> The module's FCC/CE certification was for the module alone.
> Your system may not meet the same performance.
>
> Measure VSWR of antenna in final assembly configuration.
> Not on the bare module.

> Reality: Reference design antennas are designed for a specific:
>   PCB material (FR4 — specific dielectric constant)
>   PCB thickness (1.6 mm typically)
>   Ground plane size (specified in reference design)
>   Copper clearance (exact keepout zone)
>
> If any of these change — the antenna resonant frequency changes.
>
> Example: Inverted-F antenna (IFA) designed for 40mm × 80mm board
> Placed on 20mm × 50mm board:
>   Ground plane change → resonant frequency shifts 150 MHz
>   Antenna is now out of band
>
> Always verify antenna performance after any board change.
> Copy + verify — not copy + assume.

> Reality:
>   Chip antenna: 0–2 dBi gain, very sensitive to nearby copper
>   External whip antenna: 2–3 dBi gain, less sensitive to copper
>   External fiberglass antenna: 3–8 dBi gain, independent of board
>
> For the same transmit power:
>   8 dBi vs 0 dBi = 6.3× more range (free space)
>
> Chip antenna in metal enclosure: -10 to -15 dBi effective gain
> External antenna through bulkhead connector: full rated gain maintained
>
> For outdoor, long-range, or enclosed deployments:

> External antenna is the only engineering choice.

> Reality: A range test on a clear day in open space tells you nothing about:
> Range in monsoon (rain attenuation at 2.4 GHz: 10+ dB/km)
> Range in summer heat (tropospheric ducting changes propagation)
> Range in urban deployment (multipath, shadowing, interference)
> Range as battery depletes (voltage drop → RF output power drop)
> Range at worst-case antenna orientation (polarisation mismatch)
>
> A proper range test covers:
> Multiple weather conditions
> Multiple orientations
> Edge of coverage — where does it fail, not where does it work
> Worst-case battery voltage
>
> Test at the edges. Not at the centre.

D-2: Antenna Fundamentals — What Every IoT Engineer Must Know

Parameter 1: Frequency & Wavelength

```
λ (wavelength) = c / f

where:
c = speed of light = 3 × 10^8 m/s
f = frequency in Hz

India IoT frequencies:
BLE / WiFi / Zigbee:  2.4 GHz  → λ = 125 mm  → λ/4 = 31.2 mm
LoRa India:            866 MHz  → λ = 346 mm  → λ/4 = 86.5 mm
NB-IoT Band 5:         850 MHz  → λ = 353 mm  → λ/4 = 88.2 mm
GPS L1:               1575 MHz  → λ = 190 mm  → λ/4 = 47.6 mm
NavIC L5:             1176 MHz  → λ = 255 mm  → λ/4 = 63.7 mm
```

> Why λ/4 matters: A quarter-wave monopole antenna over a ground plane resonates at its design frequency. This is the simplest, most common IoT antenna. Getting the physical length right is the first step.

Parameter 2: Impedance & VSWR

```
Standard RF impedance: 50Ω everywhere in IoT

VSWR = (1 + |Γ|) / (1 - |Γ|)
Reflection coefficient Γ = (ZL - Z0) / (ZL + Z0)

VSWR 1:1  = perfect match — all power reaches antenna
VSWR 2:1  = 11% power reflected — acceptable
VSWR 3:1  = 25% power reflected — marginal
VSWR 6:1  = 51% power reflected — unacceptable
```

Parameter 3: Gain

```
Common antenna gains:
Chip antenna:                    0-2 dBi (omnidirectional)
PCB trace (IFA):                 1-3 dBi (directional)
Rubber duck whip:                2-3 dBi (omnidirectional)
Quarter-wave monopole:           2.15 dBi (omnidirectional)
Fiberglass omnidirectional:      5-8 dBi (compressed pattern)
Yagi directional:                8-14 dBi (highly directional)
Patch antenna (GPS):             3-5 dBi + LNA (directional upward)

What gain means in range:
Every 6 dB increase in antenna gain → 2× range (free space)
Chip antenna (0 dBi) → fiberglass (6 dBi) = 2× range
Chip antenna (0 dBi) → directional (12 dBi) = 4× range
BUT only in the direction the antenna points.
```

Parameter 4: Radiation Pattern

```
Omnidirectional antenna:          Directional antenna:
(Rubber duck, whip)               (Yagi, patch)

All horizontal directions equal   Power concentrated forward
Good for: sensor nodes            Good for: point-to-point links
          unknown orientation               gateway to gateway
          mobile assets                     known fixed direction
```

Parameter 5: Polarisation

> Linear polarisation: antenna radiates in one plane — horizontal or vertical.
>
> Cross-polarisation loss:
> Transmit: vertical polarisation, Receive: horizontal polarisation
> Loss: 20–30 dB — catastrophic link loss
>
> In IoT practice:
> All infrastructure (gateway) antennas: vertical polarisation
> End node antennas must also be vertical when possible
> Wearables: body orientation varies — budget 6 dB polarisation margin for unknown orientation nodes

Parameter 6: Bandwidth

> Antenna bandwidth = frequency range where VSWR < 2:1
>
> Narrow bandwidth antennas: Half-wave dipole 5% BW, IFA on 40mm board 3% BW
> Wide bandwidth antennas: Log-periodic 50%+ BW, Wideband monopole 20% BW
>
> At 866 MHz LoRa: 5% bandwidth = 866 ± 43 MHz — covers India LoRa band (865–867 MHz) easily
>
> For multi-band devices (LoRa + NB-IoT + GPS):
> Use separate antennas — or wideband antenna with reduced gain on each band.
> Never use a narrowband antenna on a multi-band radio.

D-3: Link Budget Calculation — LoRa 865 MHz India — Step by Step

> A link budget is an accounting of all the gains and losses in an RF communication link.
>
> It answers: 'Given my transmitter power, my antennas and my environment —
> what is the maximum range I can achieve? And what range should I design for?'
>
> Without a link budget: you are guessing range based on datasheet numbers.
> With a link budget: you know your range before you build.

The Link Budget Equation

```
Link Margin (dB) = EIRP - Path Loss - Required Receiver Sensitivity - Fade Margin

Where:
EIRP = Transmitter Power (dBm) + Antenna Gain (dBi) - Cable/Connector Loss (dB)

Path Loss = Free Space Path Loss + Environmental Loss

Fade Margin = safety margin for fading, interference, antenna orientation
  Typically: 10-20 dB for robust IoT link

If Link Margin > 0: link closes — communication works
If Link Margin < 0: link fails — system does not work
```

Worked Example — LoRa India 866 MHz

```
SYSTEM PARAMETERS:
Transmitter: STM32WL55 — India LoRa node
TX Power: +22 dBm (maximum, within WPC India EIRP limit)
Frequency: 866 MHz (India WPC band)
Spreading Factor: SF12 (maximum range, minimum data rate)
Bandwidth: 125 kHz   Coding Rate: 4/8

STEP 1: CALCULATE EIRP
TX Power:                 +22 dBm   (STM32WL at maximum)
Antenna gain:             +2 dBi    (simple whip monopole)
Cable + connector loss:   -0.5 dB   (short U.FL pigtail)
─────────────────────────────────────────────────────────
EIRP:                     +23.5 dBm
WPC India EIRP limit:     +30 dBm   ✓ Within limit

STEP 2: RECEIVER SENSITIVITY
LoRa SF12, BW125, CR 4/8:
Receiver sensitivity: -137 dBm    (from STM32WL datasheet)

STEP 3: SYSTEM GAIN
System Gain = EIRP - Sensitivity = 23.5 - (-137) = 160.5 dB

STEP 4: FREE SPACE PATH LOSS (FSPL)
FSPL (dB) = 20×log10(d) + 20×log10(f) + 32.44
            where d = distance in km, f = frequency in MHz

At  1 km:  FSPL =  91.7 dB
At  5 km:  FSPL = 105.7 dB
At 10 km:  FSPL = 111.7 dB
At 15 km:  FSPL = 115.2 dB

STEP 5: FADE MARGIN
Urban India (dense buildings):   30–40 dB additional loss
Suburban India (mixed):          20–25 dB additional loss
Rural India (open farmland):     10–15 dB additional loss

STEP 6: PRACTICAL RANGE CONCLUSIONS
Urban deployment:  System gain 160.5 dB - FSPL - urban loss - fade margin
→ Realistic: 500m–1.5 km

Rural deployment: System gain 160.5 dB - FSPL at 5km - rural loss - fade margin
→ Realistic: 8–12 km (earth curvature + terrain limits theoretical value)
```

The Link Budget Reality Table — India

Environment	Antenna	Gateway Height	Expected LoRa Range	Design For
Dense urban — Mumbai, Delhi	Whip 2 dBi	5m (rooftop)	200–500m	300m cells
Urban — Tier 2 city	Whip 2 dBi	10m	500m–1.5 km	800m cells
Suburban — mixed buildings	Whip 2 dBi	15m	1–3 km	2 km cells
Industrial estate	Whip 2 dBi	20m	2–5 km	3 km cells
Open farmland — flat	Fiberglass 5 dBi	30m on tower	8–12 km	8 km cells
Hilly terrain	Fiberglass 5 dBi	50m on hilltop	5–8 km	5 km cells
Underground (godown/pipe)	Internal — N/A	N/A — use NB-IoT	N/A	NB-IoT only

Link Budget Tools

Tool	What It Does	Link
Semtech LoRa Calculator	LoRa link budget + time on air	loratools.nl/#/airtime
Pasternack Link Budget Calculator	Generic RF link budget	pasternack.com/t-calculator-link-budget.aspx
TTN Coverage Map India	Real LoRaWAN coverage in India	ttnmapper.org
Splat! RF Propagation	Terrain-aware propagation prediction	splat.sourceforge.net
Radio Mobile	RF coverage simulation	radiomobile.pe1mew.nl

D-4: Antenna Selection Guide — Every IoT Frequency Used in India

Application	Frequency (India)	Antenna Type	Gain	Connector	Key Specification	Avoid
LoRa rural gateway	865–867 MHz	Fiberglass omnidirectional — pole mounted	5–8 dBi	N-type female	VSWR < 1.5:1, IP67, lightning protected	Rubber duck indoors
LoRa end node — field	865–867 MHz	Monopole whip or PCB trace	0–3 dBi	U.FL or SMA	Resonance at 866 MHz, VSWR < 2:1	Random unterminated wire
LoRa — underground	865–867 MHz	External whip above ground	2–3 dBi	SMA bulkhead	IP68 bulkhead connector, cable loss < 1 dB	Any internal antenna
WiFi IoT device	2.4 GHz + 5 GHz	PCB trace IFA or chip antenna	2–3 dBi	U.FL or integrated	Keepout respected, VSWR < 2:1, no copper under	Metal enclosure without cutout
BLE wearable	2.4 GHz	Inverted-F Antenna (IFA) on PCB	0–2 dBi	Integrated	Body proximity detuning characterised	Chip antenna near metal strap
NB-IoT underground	700–850 MHz	External flexible LTE	1–3 dBi	SMA bulkhead	Multiband — Band 5 (850) + Band 28 (700)	Single-band antenna on multiband modem
NB-IoT outdoor	700–850 MHz	Blade LTE antenna	2–4 dBi	SMA	IP67, UV stable, multi-band	WiFi antenna — wrong band
4G vehicle	700–2100 MHz	Magnetic mount multiband	3–5 dBi	SMA	Ground plane required — vehicle roof, multi-band VSWR < 2:1	Edge mount — no ground plane
GPS / NavIC	1575 + 1176 MHz	Active patch ceramic	3–5 dBi + LNA	U.FL	Active LNA 28–40 dB gain, IP67 outdoor, clear sky view	Passive antenna with long cable
Indoor AQI node	865 MHz + 2.4 GHz	Dual-band chip antenna	1–2 dBi each	Integrated	Dual-band operation verified	Single-band antenna
Satellite (Iridium)	1616–1626.5 MHz	Patch or blade — omnidirectional	2–4 dBi	SMA	Wide-angle coverage, IP67, lightning protected	Directional — satellites move

India-Specific RF Frequency Allocation

Technology	India Frequency	WPC Approval	Max EIRP	Critical Note
LoRa / LoRaWAN	865–867 MHz	Not required for < 1W EIRP	1W (30 dBm)	NOT 868 MHz — that is the European band

Technology	India Frequency	WPC Approval	Max EIRP	Critical Note
WiFi 2.4 GHz	2400–2483.5 MHz	Not required	100 mW (20 dBm)	Channels 1–13 permitted in India
WiFi 5 GHz	5180–5825 MHz	Not required (indoor)	200 mW (23 dBm)	Outdoor use restricted on some sub-bands
BLE	2400–2483.5 MHz	Not required	100 mW (20 dBm)	Shared with WiFi — coexistence design required
NB-IoT	Carrier assigned bands	Not required (via carrier)	Carrier managed	Requires SIM from TRAI licensed carrier
4G LTE	Carrier assigned	Not required (via carrier)	Carrier managed	Requires SIM
GPS	1575.42 MHz	Not required (receive only)	Passive receive	NavIC addition strongly recommended
NavIC	1176.45 + 2492 MHz	Not required (receive only)	Passive receive	India sovereign — always include
Satellite uplink	Various	WPC type approval required	Carrier managed	Iridium/VSAT requires WPC approval

D-5: Multi-Wireless Board Antenna Placement — The Rules That Prevent Self-Interference

> A board with WiFi + BLE + LoRa + GPS (very common in Indian IoT products) has four radios operating simultaneously.
>
> Without proper antenna placement:
> WiFi transmit desensitises BLE receiver (same 2.4 GHz band)
> LoRa transmit couples into GPS receiver front end
> BLE transmit causes GPS position error
>
> Antenna placement is not aesthetic.
> It is electromagnetic engineering.
> Get it wrong — you have a product that works in isolation and fails in deployment.

Rule 1: Minimum Antenna-to-Antenna Spacing

```
Minimum separation = λ/4 at the lower frequency of the pair

LoRa (866 MHz) to WiFi/BLE (2.4 GHz):   λ/4 at 866 MHz = 86 mm minimum
LoRa (866 MHz) to GPS (1575 MHz):        λ/4 at 866 MHz = 86 mm minimum
WiFi (2.4 GHz) to BLE (2.4 GHz):        Same band — time-division preferred
NB-IoT (850 MHz) to GPS (1575 MHz):      λ/4 at 850 MHz = 88 mm minimum

PRACTICAL RULE:
On a board < 100mm × 100mm with multiple antennas:
  Place antennas on different edges
  Use ground slot for isolation
  Verify with S21 measurement < -25 dB between ports
```

Rule 2: Antenna Placement on Board Edges

```
CORRECT PLACEMENT:

Board layout:
┌──────────────────────────────────────────┐
│                                          │
│   [LoRa]                    [GPS]        │
│   antenna                   patch        │
│   SMA at                    U.FL at      │
│   left edge                 top edge     │
│                                          │
│   [MCU]  [Power]  [Connectors]           │
│                                          │
│   [WiFi]                                 │
│   chip ant                               │
│   at bottom                              │
│   left corner                            │
└──────────────────────────────────────────┘

Three different edges — maximum separation
Each antenna on a different edge — orthogonal placement
GPS faces upward — sky view requirement met
```

Rule 3: Ground Slot Isolation

```
Ground slot = cut in ground plane between antenna zones
Acts as electromagnetic barrier — 10-15 dB additional isolation

      LoRa          WiFi
     antenna       antenna
        │             │
════════╪══[SLOT]═══╪═════  Layer 2 Ground Plane
        │             │
   LoRa radio      WiFi radio

SLOT DIMENSIONS:
Length: λ/4 at interfering frequency
Width: 1-2 mm
Bridge slot at one point with 0Ω resistor for DC continuity
```

Rule 4: Component Clearance from Antenna

Component	Minimum Clearance	Why
Electrolytic capacitor	15mm	Carbon in capacitor body absorbs RF
Battery	20mm	Carbon + electrolyte absorbs RF
Display / LCD	30mm	Metal frame + backlight cables detune antenna
Metal shield can	25mm	Reflection and blockage
USB connector (metal)	20mm	Acts as parasitic element
Any copper pour	Per keepout zone	Copper on any layer under antenna detunes
Via stitching	Per keepout zone	Vias under antenna radiating element — move outside keepout

Rule 5: Test All Radios On Simultaneously

```
The most important test nobody does:

STEP 1: Measure LoRa VSWR with LoRa only active
STEP 2: Turn on WiFi at full power — measure LoRa VSWR again
STEP 3: Turn on BLE — measure LoRa VSWR again
STEP 4: All radios on — measure VSWR of each

If VSWR changes > 0.3 when other radios activate:
  Antenna coupling problem — redesign placement
  Add ground slot between antenna zones
  Increase physical separation

Isolation test (S21) between antenna ports:
  Connect NanoVNA port 1 to LoRa antenna
  Connect NanoVNA port 2 to WiFi antenna
  Measure S21 at LoRa frequency
  Target: < -25 dB
  Fail: > -15 dB — redesign required
```

Rule 6: WiFi + BLE Coexistence at 2.4 GHz

> WiFi and BLE share the 2.4 GHz band. They cannot both transmit simultaneously without coordination.
>
> Hardware coexistence methods:
>
> 1. Single antenna sharing — RF switch, time-division:
> Less hardware — one antenna
> Requires Packet Traffic Arbitration (PTA)
> ESP32 has built-in coexistence — enable in firmware
> nRF5340 + WiFi chip: use PTA lines between chips
>
> 2. Separate antennas — spatial isolation:
> Two antennas, 40mm+ separation
> Reduces interference but does not eliminate it
> Requires frequency management in software
>
> For most IoT products:
> Single antenna with PTA coexistence is the correct approach.
> Two 2.4 GHz antennas without PTA = worse performance than one.

D-6: Enclosure Effects on Antenna Performance

The Enclosure Antenna Interaction Table

Enclosure Material	Effect on 2.4 GHz	Effect on 866 MHz	Mitigation
Natural / white ABS	-1 to -2 dB gain loss	-0.5 to -1 dB	Acceptable — test and verify
Grey or coloured ABS	-2 to -4 dB	-1 to -2 dB	Test — carbon black pigment absorbs RF
Carbon-black black ABS	-8 to -15 dB — catastrophic	-5 to -10 dB	Never use near antenna — use antenna window
Polycarbonate (clear)	-0.5 to -1 dB	-0.5 dB	Best choice for enclosure over antenna
Metal enclosure — aluminium	Total blockage	Total blockage	External antenna + bulkhead connector mandatory
Metal enclosure — SS	Total blockage	Total blockage	External antenna + bulkhead connector mandatory
Fibreglass (GRP)	-1 to -2 dB	-0.5 to -1 dB	Good outdoor enclosure material
IP67 sealed gasket	Minimal if non-metallic	Minimal	Avoid metallic foil gaskets near antenna

The Antenna Window Concept

```
METAL ENCLOSURE WITH ANTENNA WINDOW:

    ┌──────────────────────────────────────────┐
    │ METAL ENCLOSURE (aluminium or SS)        │
    │                                          │
    │   ┌──────────────┐                       │
    │   │ PCB + circuit│                       │
    │   └──────┬───────┘                       │
    │          │   RF cable                    │
    │          │                               │
    │   ┌──────┴───────┐          Bulkhead SMA │
    │   │ ← Antenna    │ ── connector ───────► │
    │   └──────────────┘          through wall │
    │   Polycarbonate                          │
    │   window — RF transparent                │
    └──────────────────────────────────────────┘

Result:
- Metal enclosure: full IP67/IP68 + mechanical protection
- Polycarbonate window: RF transparent — antenna performance maintained
- Bulkhead connector: connects internal PCB to external antenna
```

The Resonant Frequency Shift in Enclosure

> When you mount your PCB + antenna inside an enclosure:
> The dielectric constant of the enclosure material
> changes the effective dielectric constant around the antenna.
>
> Effect: Antenna resonant frequency shifts DOWN
> (plastic slows the wave — shortens effective wavelength)
>
> Magnitude:
>   ABS enclosure 3mm thick over antenna: -50 to -150 MHz shift at 2.4 GHz
>   Polycarbonate 2mm: -30 to -80 MHz shift at 2.4 GHz
>
> Solution:
>   Design antenna 2–5% shorter than free-space calculation
>   Verify VSWR in final assembly configuration — not in open air
>   Add tuning stub if frequency shift too large

The Mandatory Enclosure Antenna Test Protocol

```
STEP 1: Measure antenna VSWR in open air (no enclosure)
  Target: VSWR < 1.5:1 at operating frequency

STEP 2: Mount PCB in enclosure without lid
  Measure VSWR again — note any shift

STEP 3: Close enclosure lid completely
  Measure VSWR — this is your operational VSWR

STEP 4: Place enclosure in final mounting position
  (On a pole, on a wall, in soil, on a vehicle)
  Measure VSWR — metal nearby may further detune

STEP 5: If VSWR > 2:1 in final configuration:
  Option A: Antenna window (polycarbonate cutout)
  Option B: External antenna + bulkhead connector
  Option C: Antenna trimming (shorten by 3–5%)
  Option D: Matching network adjustment (LC match)

DOCUMENT: Record VSWR at each step — comparison shows effect of enclosure
```

D-7: NanoVNA Practical Guide — Measure Your Antenna Before You Deploy

> NanoVNA = Nano Vector Network Analyser
> Cost: ₹2,000–₹4,000 on Amazon India
> Measures: S11 (return loss / VSWR) and S21 (insertion loss / isolation)
>
> For antenna work, you primarily use S11:
>   S11 =   0 dB: all power reflected (worst — open or short)
>   S11 = -10 dB: 10% reflected, 90% radiated (VSWR ≈ 1.9:1 — acceptable)
>   S11 = -20 dB: 1% reflected, 99% radiated (VSWR ≈ 1.2:1 — excellent)
>   S11 = -∞:   all power radiated (VSWR = 1:1 — perfect match)

The NanoVNA Calibration Procedure — Mandatory Before Every Measurement

```
EQUIPMENT NEEDED:
- NanoVNA V2 or H4 (V2 preferred)
- SMA calibration kit: Open, Short, Load (50Ω)
- SMA cable — RG316 or similar, < 30cm

CALIBRATION STEPS:
1. Connect SMA cable to NanoVNA PORT 1 (CH0)
2. Set frequency range:
   - LoRa 866 MHz: 700 MHz – 1100 MHz
   - WiFi/BLE 2.4 GHz: 2000 MHz – 3000 MHz
   - Multiband: 700 MHz – 3000 MHz
3. OPEN calibration:
   - Attach OPEN terminator to cable end
   - Press CALIBRATE → OPEN → confirm
4. SHORT calibration:
   - Attach SHORT terminator
   - Press CALIBRATE → SHORT → confirm
5. LOAD calibration:
   - Attach 50Ω LOAD terminator
   - Press CALIBRATE → LOAD → confirm
6. SAVE calibration to slot 0

⚠ Recalibrate every time you change frequency range.
⚠ Recalibrate every time you change the cable.
⚠ A NanoVNA without calibration gives meaningless results.
```

Reading the NanoVNA — What to Look For

```
DISPLAY OPTIONS:
VSWR Plot:        Shows VSWR vs frequency — look for minimum
Return Loss:      Shows S11 in dB — look for deepest dip (most negative)
Smith Chart:      Shows impedance — centre = 50Ω = perfect match

VSWR PLOT — what to look for:
  3 ──────────────────────────────────────────
  |
  2 ─────────────────┐───────────────────────   ← VSWR 2:1 limit
  |                  |
  1 ─────────────────└───────────────────────
  |                  ↑
  |             Resonant frequency
  |          (deepest dip = best match)

ACCEPTANCE CRITERIA:
VSWR < 2:1 across your operating frequency band
VSWR < 1.5:1 at your exact operating frequency
Resonant frequency within ± 2% of target frequency

COMMON PROBLEMS AND DIAGNOSIS:
VSWR never < 2:1 anywhere:
  → Antenna not connected / open circuit / connector fault

VSWR minimum at wrong frequency:
  → Antenna wrong length / wrong board size / enclosure effect
  → Action: trim antenna (shorter = higher frequency)

VSWR dip is very narrow (< 1% BW):
  → Antenna too close to ground plane
  → Action: increase antenna-to-ground clearance

VSWR flat — no dip:
  → Short circuit / DC path through connector
  → Action: check for solder bridge at connector
```

Practical Measurement Scenarios

Scenario 1: Measuring LoRa Node Antenna at 866 MHz

```
1. Calibrate NanoVNA: 700-1100 MHz
2. Connect to LoRa antenna port of node PCB
3. Display: VSWR plot
4. Look for VSWR minimum near 866 MHz
5. Record: minimum VSWR + frequency of minimum
6. If VSWR minimum is at 900 MHz (European default):
   a. Hardware: trim PCB trace antenna shorter by 3-4%
   b. Software: ensure radio set to 866 MHz
      (some modules default to European 868 MHz)
7. Document: date, configuration, VSWR value, resonant frequency
```

Scenario 2: Measuring Isolation Between LoRa and WiFi Antennas (S21)

```
1. Calibrate NanoVNA: 700–3000 MHz (covers both bands)
2. Connect PORT 1 to LoRa antenna connector
3. Connect PORT 2 to WiFi antenna connector
4. Display: S21 (Logmag)
5. Measure at 866 MHz and at 2400–2500 MHz
6. Target: S21 < -25 dB at all frequencies
7. If S21 > -20 dB:
   a. Increase physical separation between antennas
   b. Add ground slot between antenna zones
   c. Check component clearances
```

NanoVNA Limitations — Know Them

Limitation	What It Means	Workaround
Accuracy: ±1–2 dB	Good for go/no-go, not precision	Accept as directional — use for comparison
Frequency range: 50 kHz – 3 GHz (V2)	Cannot measure 5 GHz WiFi	Use NanoVNA SAA-2N for 5 GHz — ₹6,000
No radiated efficiency measurement	Cannot measure total radiated power	Use ERTL/SAMEER anechoic chamber for TRP
Requires calibration	Uncalibrated = useless	Always calibrate — every session
Cannot measure in enclosure (external port only)	Must have RF connector to measure	Add U.FL connector for measurement — remove after

D-8: Antenna Vendors with India Presence

Vendor	Antenna Types	India Availability	Key Products for IoT	Link
Taoglas	Flexible, PCB, patch, blade — premium	Mouser India	FXP73 (LoRa), FLP.01 (GPS+NavIC), FXUB63 (multiband LTE)	taoglas.com
Molex Antenna	Flexible, blade, magnetic mount	Mouser India	2042810100 (2.4 GHz), 2042810300 (LTE)	molex.com/en-us/products/antennas
Linx Technologies	PCB, chip, whip — good value	Digi-Key India	ANT-868-CW-HWR (LoRa), ANT-2.4-CW-RCL (BLE)	linxtechnologies.com
Amphenol RF	Connectors + antennas — industrial	Mouser India	132289 (N-type fiberglass), SMA series	amphenolrf.com
Abracon	Chip antennas, crystals	Mouser India	ACAG0603-863-T (LoRa chip), ACAG0603-2450-T (BLE)	abracon.com
Huber+Suhner	High performance, industrial	Mouser India	SENCITY Road (vehicle), MXHSA series	hubersuhner.com
Panorama Antennas	Vehicle, IoT multiband	element14 India	LGMM-G-5-27-SMA (multiband vehicle)	panorama-antennas.com
RF Solutions	LoRa, IoT antennas	element14 India	ANT-868-SP (LoRa), ANT-2.4-SP (2.4 GHz)	rfsolutions.co.uk
Quectel	GNSS antennas + NavIC modules	Mouser India	GNSS patch + LC29H NavIC receiver module	quectel.com

The Connector Reference Table

Connector	Use Case	Mating	Key Spec	Warning
U.FL (IPEX MHF)	PCB-to-module — internal	Snap-fit — 30 cycles max	50Ω, 6 GHz max	Fragile — do not over-flex cable
MHF4 (IPEX)	Ultra-miniature — wearables	Snap-fit	50Ω, 6 GHz, smaller than U.FL	Even more fragile than U.FL
SMA female	External antenna connection	SMA male antenna	50Ω, 18 GHz, standard	—
N-type female	Gateway, outdoor, high power	N-type male	50Ω, 18 GHz, weatherproof	—
RP-SMA	WiFi routers only	RP-SMA male	50Ω — reverse polarity	INCOMPATIBLE with SMA — appears connected but no RF contact
SMA bulkhead	IP67 enclosure through-connector	SMA on both sides	IP67 gasket sealed	Verify IP rating of specific part
BNC	Test equipment connection	BNC male	50Ω, 4 GHz	Low frequency limit — not for 5 GHz

> *RP-SMA Warning: RP-SMA (Reverse Polarity SMA) is used on WiFi routers. It is mechanically compatible with SMA but electrically reversed. An SMA antenna on an RP-SMA connector appears connected but has NO RF contact. Always verify connector type before ordering.*

D-9: Must-Read Antenna Design Application Notes

Document	Publisher	What It Covers	Link
ESP32 Hardware Design Guidelines	Espressif	PCB antenna design, keepout zone, layout rules	espressif.com/sites/default/files/documentation/esp32_hardware_design_guidelines_en.pdf
nRF52840 Antenna Tuning — AN64	Nordic Semiconductor	BLE antenna design, matching, testing on nRF	infocenter.nordicsemi.com/pdf/nAN64.pdf
CC13xx PCB Antenna Design — SWRA117D	Texas Instruments	Sub-GHz PCB antenna for LoRa-band applications	ti.com/lit/an/swra117d/swra117d.pdf
SX1276 LoRa Hardware Design Guide	Semtech	LoRa antenna, matching network, PCB layout	Semtech product page — search SX1276 design guide
STM32WL RF Design Guide — AN5409	STMicroelectronics	STM32WL LoRa RF layout, matching, component BOM	st.com/resource/en/application_note/an5409.pdf
Taoglas Antenna Fundamentals	Taoglas	Complete IoT antenna guide — beginner to advanced	taoglas.com/antenna-fundamentals
LoRa Alliance Coverage Guide	LoRa Alliance	LoRaWAN coverage planning, link budget calculation	lora-alliance.org/resource_hub
Quectel LC29H Hardware Design	Quectel	NavIC + GPS multi-constellation receiver design	quectel.com — search LC29H
IPC-2141A Controlled Impedance	IPC	PCB trace impedance for RF — the standard reference	ipc.org/ipc-2141

Document	Publisher	What It Covers	Link
Murata Antenna Design Guide	Murata	Chip antenna placement, keepout, matching network	murata.com — search chip antenna design guide

> The three application notes every student must read before designing any wireless PCB:
>
> 1. Your radio chip's PCB design guide
> Every radio manufacturer publishes this — non-optional reading.
> Contains: keepout zone dimensions, ground plane requirements,
> matching network component values, layout recommendations.
>
> 2. Taoglas Antenna Fundamentals
> Free, comprehensive, well-illustrated.
> Covers: all antenna types, frequency matching, enclosure effects, testing.
>
> 3. LoRa Alliance Coverage Planning Guide (for any LoRa deployment)
> Covers: link budget, coverage prediction, gateway placement.

The Antenna Engineering Checklist — Faculty Use Before Approving Any Wireless Project

☐ Is the antenna designed for the correct India frequency? LoRa: 866 MHz (NOT 868 MHz). WiFi: 2.4 GHz channels 1–13. NB-IoT: Band 5 (850 MHz) / Band 28 (700 MHz).

☐ Has the link budget been calculated? TX power + antenna gain - path loss - fade margin = link margin > 10 dB. Show the calculation.

☐ Is the antenna keepout zone respected on all copper layers? No copper — any layer — under the antenna radiating element.

☐ Has VSWR been measured with NanoVNA in final assembly? VSWR < 2:1 at operating frequency — in enclosure — in mounting position.

☐ For multi-wireless boards — is isolation between antennas measured? S21 < -25 dB between any two antenna ports.

☐ Is the enclosure material RF-transparent near the antenna? No carbon-black plastic. No metal near antenna. Polycarbonate window if needed.

☐ Is there a bulkhead connector for outdoor or enclosed deployments? Internal chip antenna inside a metal or opaque enclosure = zero range.

☐ Has the range been verified in real deployment conditions? Not in open lab. In actual environment: urban, agricultural, industrial, or underground.

☐ For LoRa: is the radio frequency configured to 866 MHz in firmware? Not left at European default 868 MHz.

☐ For GPS/GNSS: is NavIC included in the constellation selection? India mandate 2024 — AIS 140 already requires NavIC.

Cross-References

For	Go to
PCB layout rules for RF traces — 50Ω impedance, ground plane, keepout zones	Appendix C: Engineering Integrity | C-11 PCB Stack-up & C-12 EMC Rules
BIS / WPC type approval for wireless products sold in India	Appendix E: Certification & Compliance
NavIC chipset options and India positioning requirement	Appendix B: Hardware Stack Reference | B-2 RF Connectivity
LoRa gateway vs NB-IoT underground node — which RF for which solution	Appendix A1–A5: Solutions Matrix — RF Primary column per solution
Pre-compliance testing — near-field scan, power profiling with NanoVNA	Appendix C: Engineering Integrity | C-19 Pre-Compliance Testing
SAMEER Chennai and Delhi — anechoic chamber for TRP measurement	Appendix C: Engineering Integrity | C-20 Accredited EMC Test Labs
All 52 solutions — RF Primary and RF Secondary per solution	Appendix A6: Master Solutions Index