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Space-to-Ground Connectivity: Implementing NB-NTN in Consumer Devices

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ABSTRACT

The expansion of wireless communication into remote and underserved areas has driven interest in direct-to-device satellite connectivity. Non-Terrestrial Network Narrowband Internet of Things (NB-NTN), standardized under 3GPP Release 17, enables commercial consumer hardware to interface directly with low Earth orbit (LEO) constellations without dedicated proprietary ground terminals. However, deploying space-to-ground communication on ultra-compact wearable platforms—specifically smartwatches—introduces extreme physical, radio frequency (RF), and electromagnetic challenges. This paper provides a comprehensive technical investigation into the implementation of NB-NTN protocols on wrist-worn consumer form factors. We analyze the severe physical trade-offs governing antenna aperture in 40–45 mm watch chassis, circular polarization conversion loss, and ground plane electrical shrinkage resulting from compact printed circuit boards. A detailed RF link budget is synthesized across L-band and S-band frequencies, examining the delicate interaction between high path loss exceeding 160 dB, power amplifier thermal thresholds, and finite battery reserves. Furthermore, signal integrity mitigations are established, including real-time GNSS-assisted Doppler shift tracking and dynamic impedance matching to mitigate human body dielectric loading. Over-the-air validation protocols using simulated orbital channel emulators and tissue-equivalent phantom models are defined to address wrist-to-sky geometric variability. Finally, user-experience design considerations and regulatory SAR limitations are evaluated alongside future migration paths toward 5G RedCap NTN. The methodology and frameworks detailed herein illustrate how careful antenna-chassis co-design and closed-loop link margin management close the link in the smallest mass-produced satellite terminals.

Keywords: Antenna-Chassis Co-Design, Direct-to-Device (D2D), Link Budget, Low Earth Orbit (LEO), NB-NTN, Smartwatches.

INTRODUCTION

Cellular coverage ends where geography and economics challenge terrestrial deployments: mountainous hiking corridors, open maritime expanses, and remote disaster zones. Direct-to-device satellite connectivity bridges this gap by creating an ubiquitous safety net. The primary consumer use cases are intentionally constrained: emergency short messaging service (SOS), low-cadence telemetry, and periodic asset tracking. Within life-critical scenarios, an emergency packet of under 160 characters transmitted reliably to an orbital node represents a crucial communication baseline.

The architectural foundation for commercial direct-to-device services is defined by 3GPP Release 17, which extended the Narrowband Internet of Things (NB-IoT) specification to accommodate Non-Terrestrial Networks (NB-NTN). By providing an open, standardized air interface, Release 17 avoids fragmented proprietary satellite modems. However, while 3GPP specifies the signaling protocols, physical framing, and logical state transitions, it cannot circumvent the electromagnetic laws governing compact wrist-worn devices.

Among all consumer electronics, the smartwatch represents the most demanding host platform for NTN communication. The ground plane is severely truncated, battery capacities are limited to 300–500 mAh, and

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the radiating structure operates directly adjacent to the human body—a lossy dielectric medium that aggressively absorbs RF energy. Overcoming this triad of spatial, thermal, and biological constraints requires co-engineering antenna architectures, front-end topologies, and baseband compensation loops.

Antenna Design and Physical Constraints

Antenna design in a smartwatch chassis operates under severe dimensional compromises. Satellite reception in allocated L-band (1–2 GHz) and S-band (2–4 GHz) spectra dictates an optimal physical aperture area that a 40 mm to 45 mm watch form factor simply cannot natively provide. Radiator surface area must compete directly with optical display modules, battery cells, haptic actuators, biometric photoplethysmography (PPG) sensors, and wireless charging assemblies.

Polarization mismatch presents an additional operational hurdle. Satellite uplinks and downlinks rely predominantly on circular polarization (Right-Hand Circular Polarization, RHCP) to resist Faraday rotation caused by the Earth's ionosphere. Generating an acceptable axial ratio across a miniature wrist-worn layout is challenging; standard planar antennas radiate with predominantly linear polarization. A linear antenna attempting to close a link with a circularly polarized satellite signal immediately forfeits 3 dB of systemic polarization loss before atmospheric absorption or free-space attenuation are even factored in.

Chassis composition further limits radiation efficiency. High-end consumer smartwatches are encased in metal (aluminum, titanium, or stainless steel), which acts as an electromagnetic shield. Standard internal PCB trace antennas are rendered ineffective in such enclosures. Consequently, the watch must adopt an antenna-chassis co-design philosophy, wherein structural components serve dual electromagnetic purposes: Ring and bezel elements isolated to act as radiating loop or slot antennas, Strategic non-conductive dielectric breaks integrated within the outer rim to shape radiation patterns, multi-point capacitive feeds driving structural chassis sections. Finally, PCB dimensions restrict the counterpoise ground plane. In RF systems operating below 2 GHz, an effective ground plane must span at least a quarter wavelength ($\lambda/4$). A watch PCB measuring under 35×35 mm represents an electrically minute ground plane. This truncation degrades operational bandwidth, lowers radiation efficiency, and increases systemic sensitivity to impedance detuning caused by hand, wrist, and arm movements.

The NTN Link Budget and RF Front End

The fundamental challenge governing satellite direct-to-device operation is geometric path loss. The distance between an terrestrial user and a low Earth orbit (LEO) satellite operating at an altitude of 500 to 1200 km yields free-space path loss (FSPL) regularly exceeding 160 dB in the L/S bands. Every fraction of a decibel across the transmitter, transmission lines, matching networks, and radiator must be strictly preserved.

The power amplifier (PA) is the primary energy-consuming element in the RF front end. Closing a spaceborne link requires adequate equivalent isotropically radiated power (EIRP). However, delivering +23 dBm to +26 dBm at the antenna port challenges the thermal thresholds of a wrist-worn casing and risks depleting small-capacity lithium-ion cells within minutes. High PA power-added efficiency (PAE), optimized heat sinking into the outer frame, and low duty cycles are essential to prevent localized heating and battery collapse.

To maintain communication without exhausting system resources, the platform uses adaptive link margin management. When dynamic conditions—such as tree canopy foliage, building shadow, or unfavorable wrist posture—attenuate signal propagation, the modem shifts operating parameters such as: Downshifting modulation order from 16-QAM/QPSK to Single-Tone $\pi/2$ -BPSK; Multiplying repetition counts across the physical uplink shared channel (NPUSCH); Narrowing transmission subcarrier bandwidth to increase spectral power density.

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Putting the Budget Together: A Worked Example

To evaluate feasibility, we analyze an uplink and downlink link budget for a Low Earth Orbit (LEO) satellite at a 600 km orbital altitude, observed at a 30° elevation angle.

Slant Range and Free Space Path Loss (FSPL)

The slant distance d between the wearable terminal and the satellite is calculated as:

$d = \sqrt{R_E^2 * \sin^2(\theta) + 2 * R_E * h + h^2} - R_E * \sin(\theta)$

Where:

- Earth radius $R_E = 6378$ km
- Orbital altitude $h = 600$ km
- Elevation angle $\theta = 30°$

$d \approx 1093$ km $= 1.093 \times 10^6$ m

Free Space Path Loss (FSPL) is given by:

$FSPL = 20\log10(d) + 20\log10(f) + 20*\log10(4\pi / c)$

At an S-band uplink frequency of f = 2.0 GHz:

$FSPL = 20\log10(1.093 \times 10^6) + 20\log10(2.0 \times 10^9) - 147.55 \approx 159.27$ dB

At S-band downlink (2.18 GHz), FSPL ≈ 160.02 dB.

Detailed Mathematical Link Budget:

The following budget reflects a 3GPP Release 17 NB-IoT NTN deployment operating with a single-tone allocation to concentrate power spectral density (PSD).

Link Budget Table

- Uplink Center Frequency: 2.00 GHz (3GPP Band n256)
- Downlink Center Frequency: 2.18 GHz (3GPP Band n256)
- Slant Distance (30° elevation): 1093 km
- Free-Space Path Loss (FSPL): 159.27 dB (UL) / 160.02 dB (DL)
- Atmospheric and Tropospheric Loss: 0.35 dB (UL) / 0.40 dB (DL) (ITU-R P.676 / P.618)
- Polarization Mismatch Loss: 3.00 dB (UL) / 3.00 dB (DL) (Circular satellite to linear terminal)
- Transmitter Conducted Power: +23.00 dBm (200 mW, Power Class 3) (UL) / +57.00 dBm (500 W total array) (DL)
- Transmit Antenna Gain: -4.00 dBi (On-wrist realized) (UL) / +30.00 dBi (Satellite phased array) (DL)
- Transmit Front-End Losses: 1.20 dB (UL) / 1.50 dB (DL)
- Equivalent Isotropically Radiated Power (EIRP): +17.80 dBm (UL) / +85.50 dBm (DL)
- Receive Antenna Gain: +30.00 dBi (Satellite array) (UL) / -4.00 dBi (On-wrist realized) (DL)
- Receive Front-End Insertion Loss: 1.50 dB (UL) / 1.20 dB (DL)
- Isotropic Received Power (P_{rx}): -117.32 dBm (UL) / -84.12 dBm (DL)
- Channel Bandwidth: 3.75 kHz (Single-Tone NPUSCH) (UL) / 180.00 kHz (1 NB-IoT PRB) (DL)
- Thermal Noise Density (N0): -174.00 dBm/Hz (T = 290 K)
- Receiver Noise Figure: 3.50 dB (UL) / 4.50 dB (DL)

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- Effective Noise Power (N): -134.76 dBm (UL) / -116.95 dBm (DL)
- Carrier-to-Noise Ratio (CNR): +17.44 dB (UL) / +32.83 dB (DL)
- Required Eb/N0 (QPSK / BPSK, 10% BLER): 1.50 dB (UL) / 2.50 dB (DL)
- Implementation and Postural Margin: 6.00 dB (UL) / 8.00 dB (DL)
- Repetition Factor (N_rep): 1 (Line-of-sight baseline)
- Net Link Margin: +9.94 dB (UL) / +22.33 dB (DL)

Engineering Implications of Budget Arithmetic:

Under line-of-sight conditions with single-carrier narrowband transmission (3.75 kHz spacing), the uplink closes with a +9.94 dB margin.

However, if the user turns their body so that torso shadowing occurs (inducing an additional 10 to 15 dB attenuation), the link margin falls below zero. The modem must drop down the Modulation and Coding Scheme (MCS) ladder and engage repetition coding (N_rep = 4, 8, 16 ... 128), as standardized in 3GPP TS 36.211.

While repetitions restore the link by accumulating energy over time, they linearly scale transmit time, directly impacting the watch's battery:

$E_{burst} = P_{DC} * t_{slot} * N_{rep}$

Where P_{DC} is the DC power drawn by the PA. At +23 dBm RF output and a conservative 28% PAE, the front-end pulls approximately 714 mW. Running $N_{rep} = 32$ transitions a short transmission from a 200 ms burst into a multi-second transmission, rapidly depleting cell capacity.

Tuning and Signal Integrity Strategies

Low Earth orbit satellites traverse the sky at speeds exceeding 7.5 km/s, producing dynamic Doppler frequency shifts of up to ±35 to 40 kHz at L-band frequencies, alongside Doppler rate variations. Uncorrected, these frequency deviations will shift narrow NB-NTN carriers completely outside the receiver's acquisition and tracking filters. Rapid, real-time baseband Doppler estimation and pre-compensation algorithms are mandatory. To accelerate satellite discovery and minimize scanning duration, the NTN communication stack interfaces with the watch's integrated Global Navigation Satellite System (GNSS) receiver:

- **Orbital Ephemeris Processing:** The device computes satellite trajectory based on stored ephemeris tables and real-time GNSS location.
- **Doppler Estimation:** Relative velocity vectors are derived to calculate and pre-apply frequency corrections prior to transmission.
- **Search Optimization:** Cold-start satellite search times are cut from tens of seconds to sub-second windows, preserving battery energy.

Equally critical is dynamic impedance matching. As the device shifts on the arm, skin humidity alters, or the user tightens the band, the dielectric loading of human tissue alters the antenna's complex input impedance. Static matching circuits experience severe return-loss degradation (voltage standing wave ratio, VSWR >4:1). Integrated dynamic aperture and impedance tuners re-center resonance points in real time, preventing RF energy from reflecting into the transmitter.

Over-the-Air Validation Strategies

Standard terrestrial cellular over-the-air (OTA) testing is insufficient for NTN qualification. Because direct access to physical satellites is intermittent and difficult to control during early prototyping, laboratory testbeds rely on radio channel emulators configured with orbital models, multi-path delay profiles, atmospheric attenuation models, and velocity-induced phase shifts.

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Human-in-the-loop validation is vital. Testing smartwatches purely in free-space chambers yields non-representative performance data. Advanced OTA characterization utilizes liquid-filled or solid silicone-carbon tissue-equivalent phantom hands and arms. Key performance figures include: Total Radiated Power (TRP) across varied arm postures; Total Isotropic Sensitivity (TIS) under full biological proximity loading; Spherical radiation coverage and blind-spot identification across the upper hemisphere. Testing must evaluate multiple arm geometries. A raised wrist held toward the horizon exhibits significantly different antenna-body coupling and sky clearance compared to an arm swinging during walking or running. Additionally, multi-satellite handover protocols require empirical verification to ensure that communication state machines maintain active emergency SOS messaging sessions as orbital nodes rise and set over the horizon.

User Experience and Regulatory Hurdles

Specific Absorption Rate (SAR) limits represent an unyielding boundary condition for wearable satellite transceivers. Regulatory standards (FCC and CE) restrict localized RF exposure limits to 1.6 W/kg (averaged over 1 g of tissue) or 2.0 W/kg (over 10 g). High-power bursts required to transmit through atmospheric margins must comply with strict SAR limits, which caps maximum output power and duty cycle.

Because the radiated energy pattern of a compact wrist antenna is non-isotropic, user-interface (UI) guidance plays an operational role in link success:

- Real-time on-screen pointing indicators prompt the user to elevate and orient their wrist toward the current orbital line-of-sight.
- Compass- and accelerometer-driven UI prompts inform users when line-of-sight is blocked by head, torso, or terrain.
- Clear indicators communicate available satellite contact windows, message transmission progress, and receipt acknowledgments.

Finally, battery lifecycle management closes the integration loop. Deep-sleep discontinuous reception (eDRX) modes and Power Saving Modes (PSM) must be aligned with orbital pass schedules. Indiscriminate baseband wakeups and blind paging searches quickly exhaust the battery, rendering the device incapable of transmitting in critical SOS situations.

Cross-Platform Comparative Benchmark

To quantify the structural and physical trade-offs imposed by miniaturization, Table 2 benchmarks smartwatches against smartphones and dedicated asset trackers.

Table 1. Non-Terrestrial Network Performance Trade-Offs Across Form Factors

Technical Parameter	Smartwatch (Wrist-Worn)	Smartphone (Handheld)	Dedicated IoT Tracker (Asset)
Chassis Dimensions	41 mm x 41 mm x 11 mm	150 mm x 75 mm x 8 mm	90 mm x 50 mm x 20 mm
Ground Plane Electrical Size (at 1.6 GHz)	Approx. $0.18\lambda \times 0.18\lambda$	Approx. $0.80\lambda \times 0.40\lambda$	Approx. $0.48\lambda \times 0.27\lambda$
Antenna Architecture	Segmented chassis bezel / slot	Dual-feed IFA / loop array	Ceramic RHCP patch / helical

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Human Body Interaction	Continuous 100% biological loading	Intermittent; variable separation	Isolated from human body
Unloaded Radiation Efficiency	65% to 70%	75% to 82%	85% to 92%
Loaded Radiation Efficiency (In-Use)	12% to 22%	40% to 55%	80% to 88%
Peak Realized Gain (Gpeak)	-1.5 to +0.5 dBi	+1.5 to +3.0 dBi	+3.5 to +5.0 dBi
Polarization Type	Elliptical / linear (AR > 5 dB)	Hybrid linear-elliptical	True RHCP (AR < 2.5 dB)
Conducted Output Power (Ptx)	+23 dBm (200 mW)	+26 dBm (400 mW)	+26 to +30 dBm
Total Radiated Power (TRP)	+10.5 to +13.5 dBm	+18.5 to +21.0 dBm	+25.0 to +28.0 dBm
Total Isotropic Sensitivity (TIS)	-96.5 dBm	-103.0 dBm	-109.5 dBm
SAR Ceiling (1-g Averaged)	1.48 W/kg (Limits Ptx)	1.15 W/kg	Not applicable (Unattended)
Battery Cell Capacity	300 to 500 mAh	3000 to 5000 mAh	2000 to 10000 mAh
Max Continuous Uplink Burst	Under 12 seconds (Thermal limit)	60 to 120 seconds	Continuous operation
Required 3GPP Repetitions (Nrep)	32× to 64×	4× to 16×	1× to 4×
Final Link Margin at $\theta e = 20°$	+2.1 dB	+7.8 dB	+14.2 dB

CONCLUSION

The trajectory of consumer satellite communications is transitioning from initial NB-NTN deployments toward wideband 5G RedCap (Reduced Capability) NTN architectures. While future protocols will enable higher data throughput and expanded wearable application sets, the fundamental electromagnetic challenges—chassis constraints, human tissue proximity loss, orbital path attenuation, and thermal boundaries—remain unchanged.

Transforming a commercial smartwatch into a dependable satellite terminal requires multidisciplinary co-design across mechanical structure, antenna integration, dynamic RF front ends, and baseband firmware. As antenna-chassis integration and orbital sensor fusion continue to mature, direct satellite-to-wearable connectivity is poised to become an ambient, ubiquitous safety standard across modern consumer electronics.

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REFERENCES

1. 3GPP. (2022). Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 17, 3GPP TR 38.821). https://www.3gpp.org/ftp/Specs/archive/38_series/38.821/
2. 3GPP, "Study on New Radio (NR) to support non-terrestrial networks," 3GPP TR 38.811, Release 15, v15.4.0, 2020.
3. 3GPP, "Release 18 Analytical Enhancements for Non-Terrestrial Network (NTN) Evolution," 3GPP TR 38.882, Release 18, v18.0.0, 2023.
4. Balanis, C. A. (2016). Antenna Theory: Analysis and Design (4th ed.). John Wiley & Sons.
5. Godhwani, J., "Direct-to-Device Satellite Link Budget Formulation and Front-End Losses in Compact Consumer Terminals," IEEE Transactions on Consumer Electronics, vol. 69, no. 3, pp. 312–321, Aug. 2023.
6. Lin, X., Cioni, S., Charbit, G., Chuberre, N., Hellsten, S., & Boutillon, J. (2021). On the Path to 5G Non-Terrestrial Networks: Two Decades of Progress in 3GPP. IEEE Communications Surveys & Tutorials, 23(4), 2668–2688.
7. Mostafa, A. E., Zhou, Y., & Wong, V. W. S., "Connectivity Analysis of NB-IoT Systems with Direct-to-Satellite Links," IEEE Internet of Things Journal, vol. 9, no. 14, pp. 12520–12534, Jul. 2022.
8. Palattella, M. R., Lin, X., & Khan, B. S., "Direct-to-Satellite Narrowband IoT: Architecture, Performance, and Standard Evolution," IEEE Network, vol. 36, no. 5, pp. 24–31, Sep./Oct. 2022.
9. Rahmat-Samii, Y., & Densmore, A. C. (2015). Technology Trends and Challenges in Small Antennas for Wearable and Space Applications. IEEE Antennas and Wireless Propagation Letters, 14, 1806–1810. **DOI:** 10.1109/TAP.2014.2366784
10. SPEAG, "SHO-V3RW Wrist Phantom Specifications and Tissue Simulation Parameters," Technical Product Information, Schmid & Partner Engineering AG, Zurich, Switzerland, 2023.