Interdisciplinary Centre for Security, Reliability and Trust

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Technical Enablers for 6G ISAC from Space and Multi-Functional Satellite Systems

Waveforms, Full-Duplex Operation and Interference Management

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Outline

01 **Motivation, Strategies & Use Cases** — CAPEX & Spectrum • LEO Sensing Challenges • MFSS & Use Cases

02 **Waveforms, CAF & SSPA Trade-Offs** — 2D CAF & ISLR • CP-OFDM vs. DVB-S2(X) Back-Off • Detection Regimes

03 **Full-Duplex & Service Hopping** — Massive D2D Arrays • ISAC vs. Comms IBFD • Service Hopping

Section 1

Motivation, MFSS Strategies & Use Cases

Why Spaceborne ISAC?

■ Fleet CAPEX Amortization

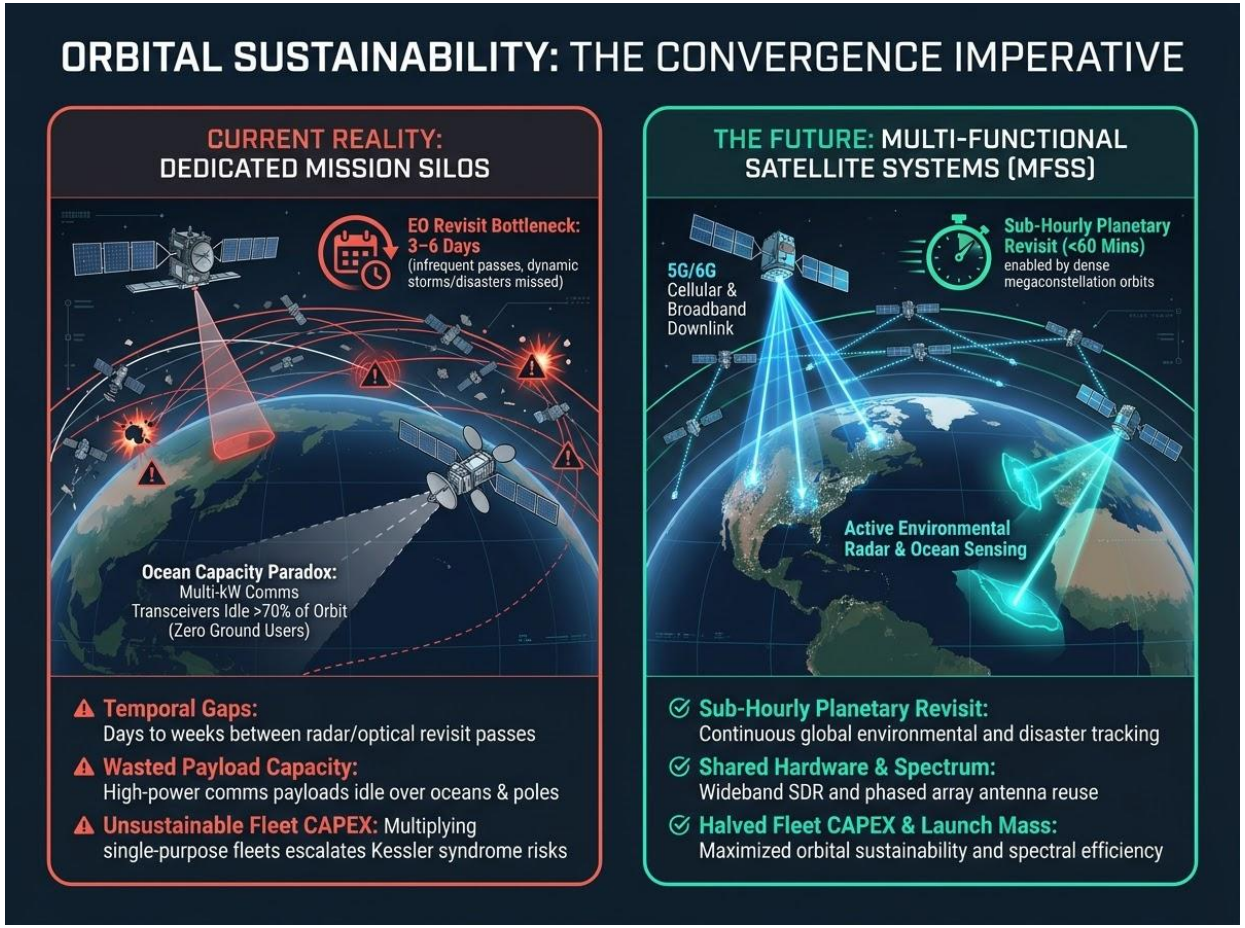
- >85% of active LEO = SatCom
- Broadband primary; skip solo EO fleets

■ Underutilized Spectrum

- ~70% of orbit over oceans & poles
- HTS (Ku/Ka) + D2D (sub-6 GHz) NTN

■ Multi-Functional Satellites (MFSS)

- Opportunistic RF sensing on idle beams
- Shared bus, SWaP & RF spectrum



Challenges of Spaceborne LEO Sensing for ISAC

■ Two-Way R^4 Echo Loss

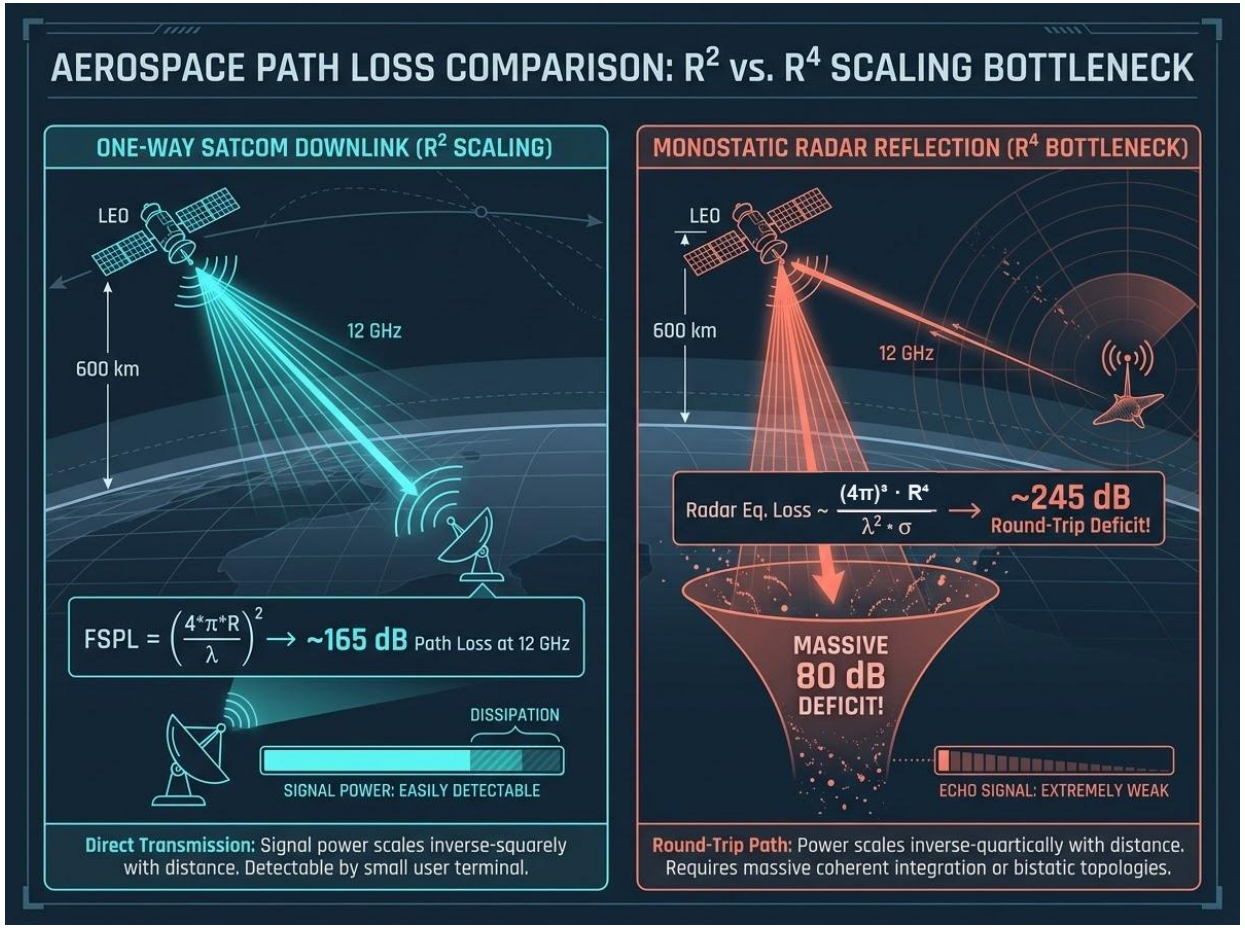
- Comms ($1/R^2$): ~170 dB path loss
- Sensing ($1/R^4$): 240–270 dB (+70–100 dB deficit)

■ Extreme LEO Doppler & Delay

- $v_{sat} \approx 7.56$ km/s → 380 kHz Ku Doppler
- Echo round-trip delay: $\tau_{RTD} \approx 4$–6 ms

■ Continuous SatCom Downlink

- 100% TX duty cycle → strong self-interference
- HPAs near saturation → waveform PAPR limit



MFSS Operational Strategies

(a) Geographical Multiplexing

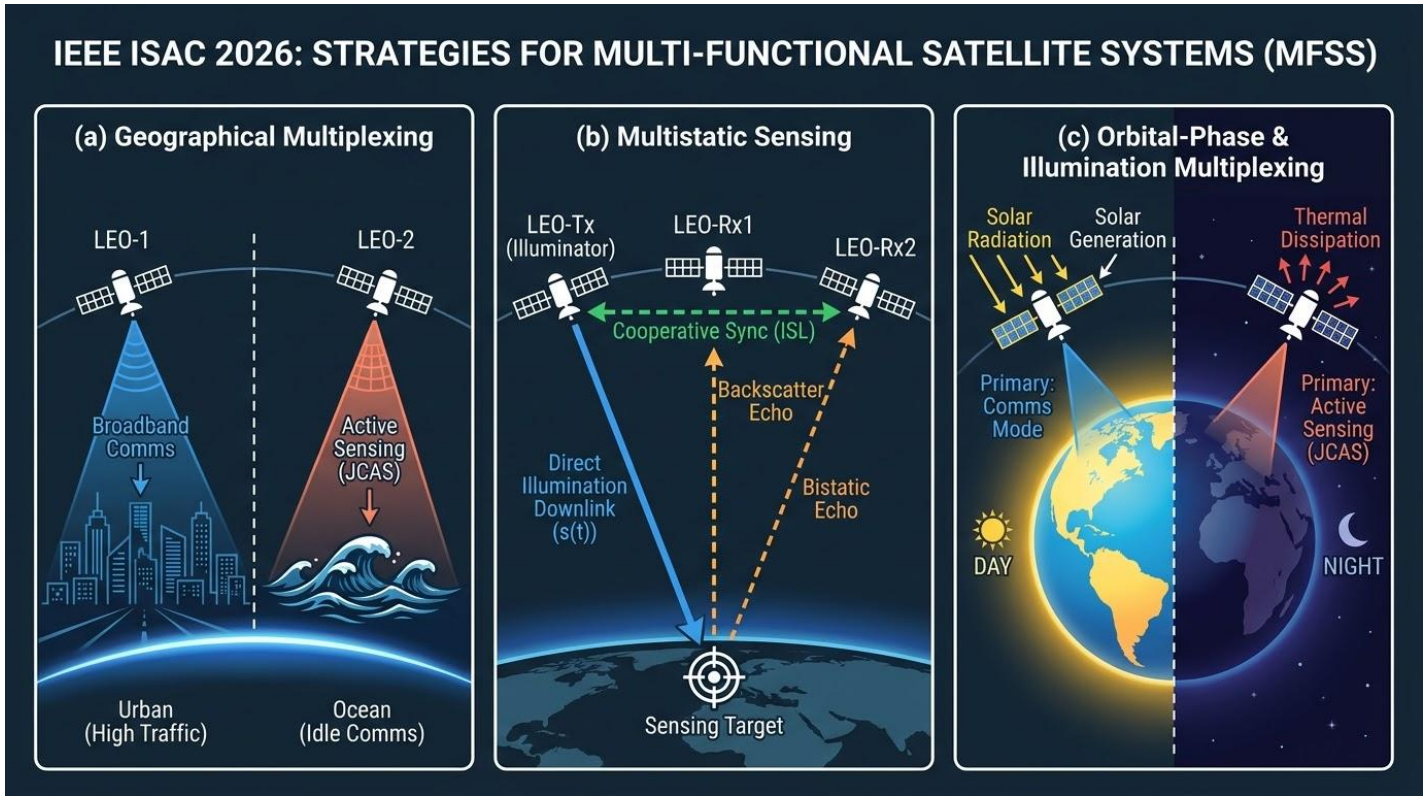
Land: Comms | Ocean/Poles: Sensing

(b) Multistatic Cooperation

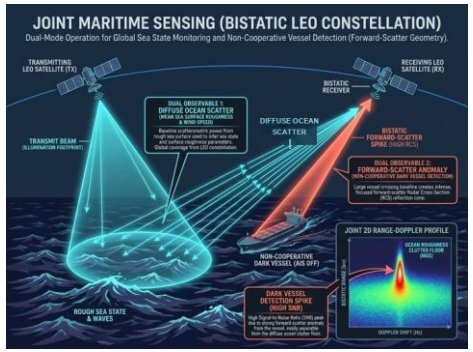
ISL sync & data share | Avoids self-interference

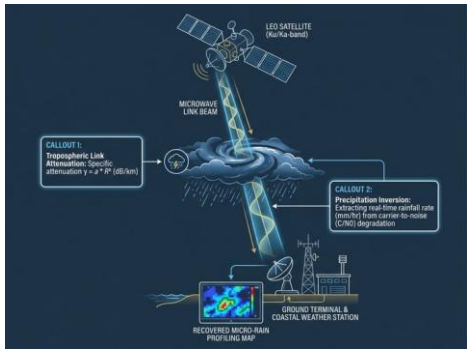
(c) Orbital-Phase Multiplexing

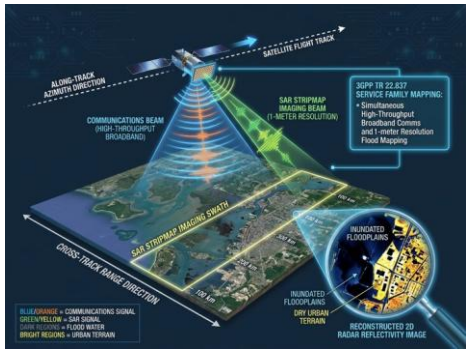
Day: Comms | Night: Sensing (cooling + optical blind)

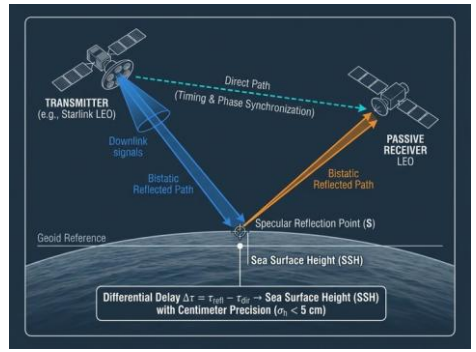


Target Spaceborne JCAS Use Cases









1. Maritime & Traffic | **2. Weather & Rain** | **3. Opportunistic SAR** | **4. Ocean Altimetry**

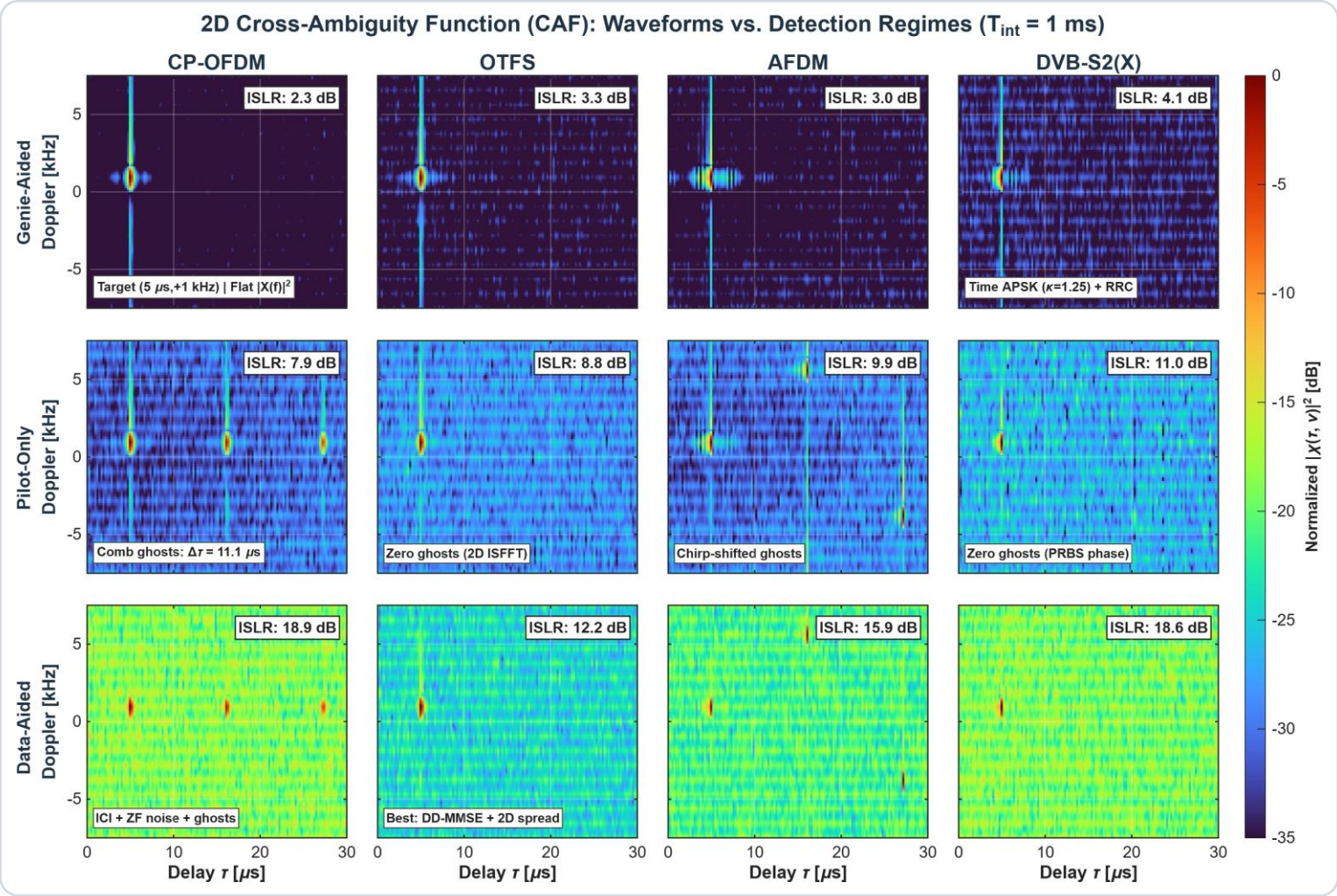
Use Case	Observable / Method	RF Bands	Key Metric / Benefit
1. Maritime & Traffic	Bragg sea-state + echoes & AIS/ADS-B	L / S / Ku / Ka	Sub-daily winds, waves, ice & vessel tracking
2. Weather & Rain	Differential rain attenuation & CSI	Ka / Q / V	3D rain cells → proactive feeder re-routing
3. Opportunistic SAR	2D pilot phase history	L / C / X / Ku	4.2 m (36 MHz) → 0.63 m (240 MHz) range res.
4. Ocean Altimetry	Specular Fresnel + diffuse delay	Ku / Ka	cm-level specular | 1.5–3 km @ 100–250 MHz

Section 2

Waveforms & SSPA Non-Linearity

Cross-Ambiguity Function (CAF) Across Waveforms

ISLR = sidelobe / mainlobe CAF energy (lower = better) | Standard DVB / 3GPP & conference waveforms



■ 1. Genie-Aided (Known TX)

- **CP-OFDM best (2.3 dB vs. 4.1 dB DVB)**
- Flattest spectral density → sharpest peak

■ 2. Pilot-Only (Unknown Data = 0)

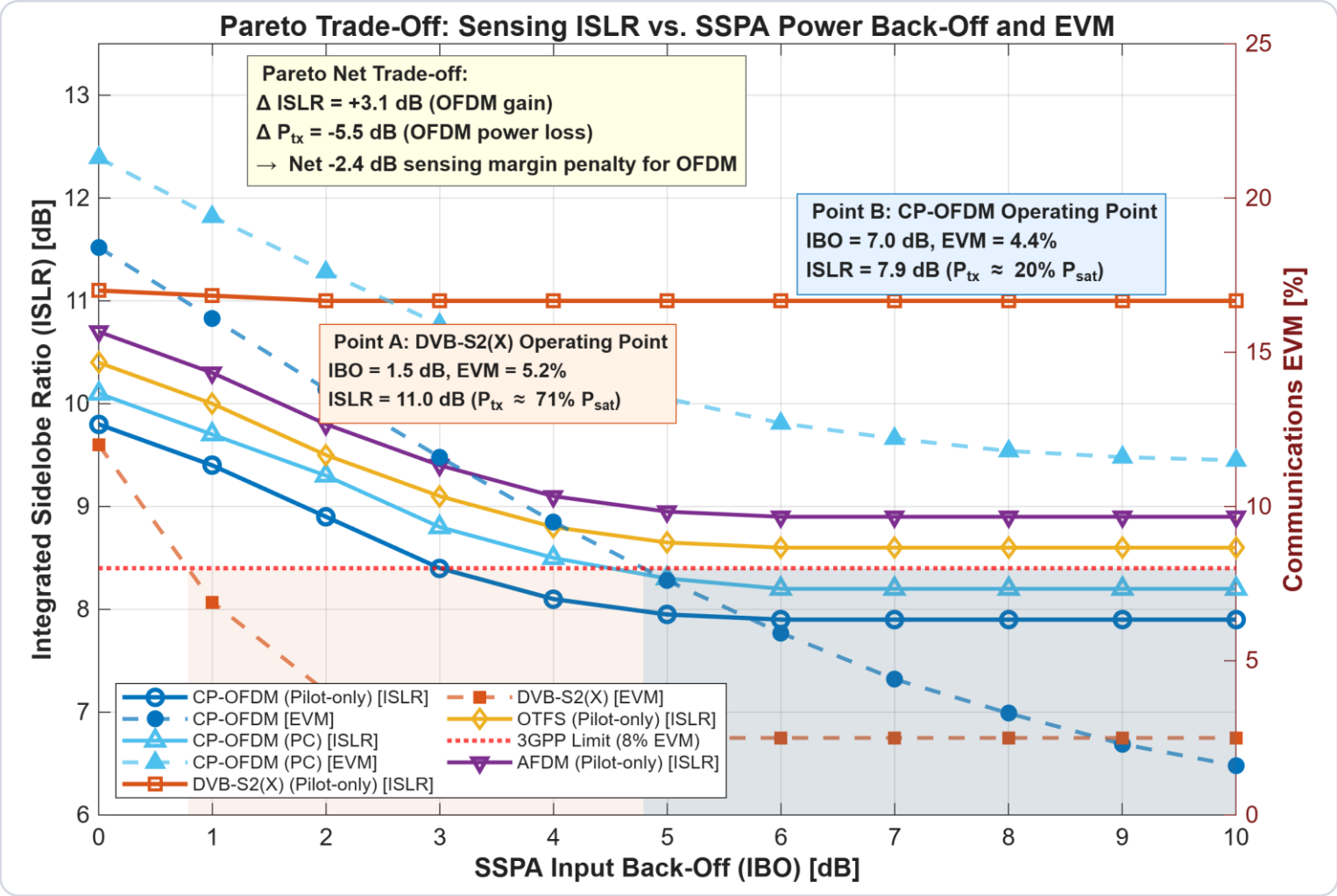
- **CP-OFDM (7.9 dB) beats DVB (11.0 dB)**
- Periodic OFDM pilots → 11.1 μs ghost peaks

■ 3. Data-Aided (Hard Decisions)

- **High floor: OFDM 18.9 dB | DVB 18.6 dB**
- Prefer Genie-Aided or Pilot-Only in practice

Pilot-Only ISLR vs. SSPA Power Back-Off

Multicarrier ISLR requires linear HPA back-off; single-carrier APSK runs near saturation (Shaded: EVM ≤ 8%)



■ DVB-S2(X) • 1.5 dB IBO

- **Single-carrier APSK → 5.3 dB PAPR**
- Pt A (71% P_sat): flat 11.0 dB ISLR

■ CP-OFDM • 7.0 dB IBO

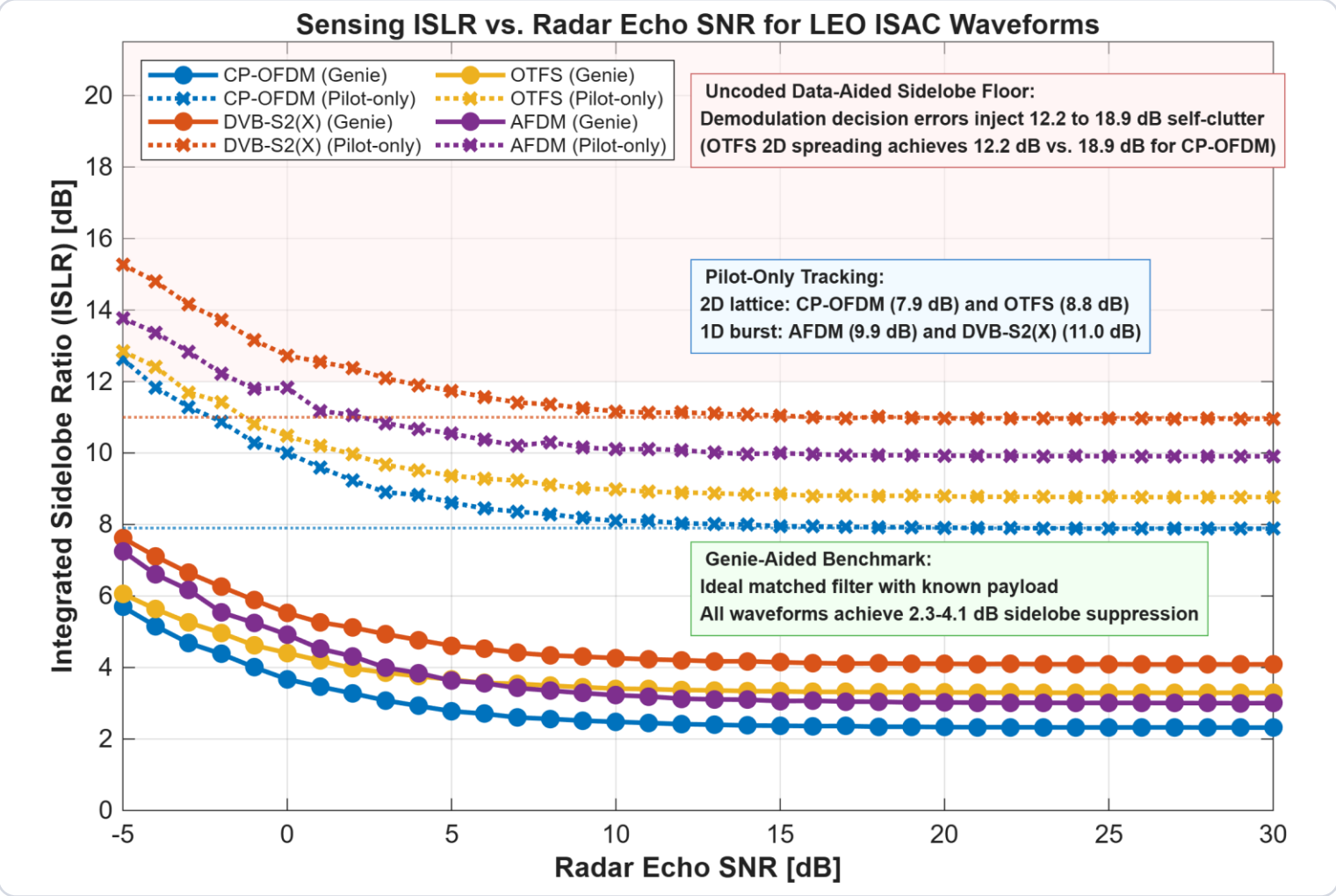
- **Multicarrier IFFT → 11.8 dB PAPR**
- Pt B (20% P_sat): needs IBO to keep 7.9 dB

■ Net Trade-Off: +2.4 dB DVB Win

- **DVB radiates +5.5 dB more RF power**
- Outweighs OFDM's 3.1 dB ISLR edge (no DPD)

Sensing ISLR Across Detection Regimes

Monostatic or OISL-shared reference unlocks Genie bound; Pilot-Only gives clean SNR-independent tracking



■ Genie-Aided (Monostatic / OISL)

- **CP-OFDM: 2.3 dB | DVB-S2(X): 4.1 dB**
- 1.8 dB gap → +3.7 dB net DVB HPA win

■ Pilot-Only (Tracking)

- **CP-OFDM: 7.9 dB | DVB-S2(X): 11.0 dB**
- OFDM has 11.1 μs ghosts; DVB is ghost-free

■ Data-Aided (Hard Demod.)

- **CP-OFDM: 18.9 dB | DVB-S2(X): 18.6 dB**
- Hard-decision errors → use Genie or Pilots

Section 3

Full-Duplex Isolation & Service Hopping

Co-Channel Interference & Massive AAS Nulling

■ Monostatic vs. Bistatic

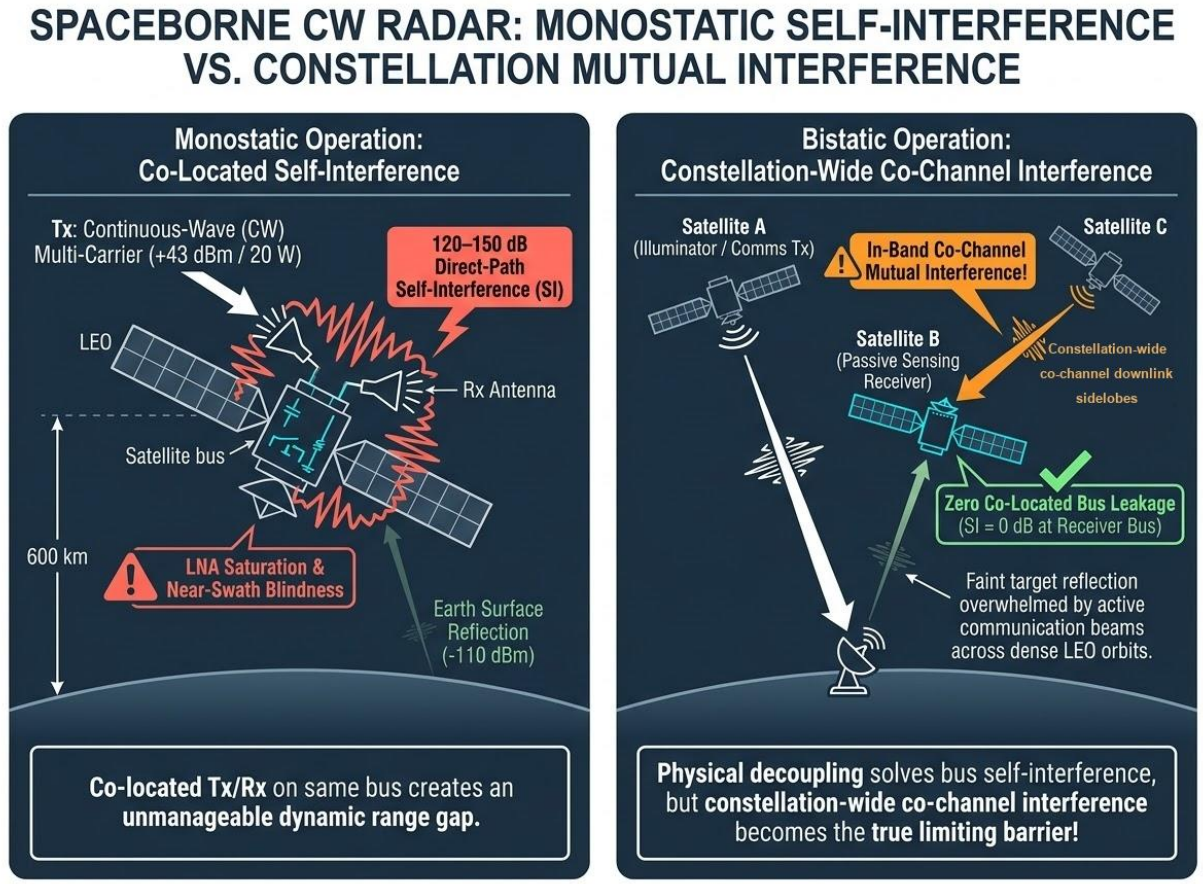
- Monostatic: Near-field bus leakage
- Bistatic / multi-orbit: +40–60 dB DPI

■ Massive D2D Phased Arrays

- 64–223 m² arrays (e.g., AST SpaceMobile)
- Narrow 1°–2° beams • SAR-class link budget

■ Spatial & Cooperative SIC

- 40–50 dB digital nulls toward RX / DPI
- OISL sharing → cooperative compensation



Spaceborne IBFD Paradox & Cascaded SIC

■ Comms IBFD: 150–160 dB

- Uplinks −95 to −112 dBm (SINR > 0)
- Heavy RF shielding mass → unfeasible

■ ISAC IBFD: Only 120–130 dB!

- Echoes −120 to −140 dBm (sub-noise)
- Feasible via wideband coherent integration

Matched-Filter Gain: $G_{proc} = 10 \log_{10}(B \cdot T) = +53.8$ dB (240 MHz) | +45.6 dB (36 MHz) → **>30 dB SIC Relief**

PASSIVE RF • 40–75 DB

Antenna Isolation

- Physical shielding (hardest: adds mass)
- Cross-pol & diplexers

→

SPATIAL • 40–50 DB

Massive AAS Nulls

- 64–223 m² phased array
- Deep digital null steering

→

CASCADED • >150 DB

Multi-Stage SIC

- ~100 dB on SDR testbeds
- >150 dB total projected

Dynamic Service Hopping (SH) & Physical Bounds

Time-domain alternative to full-duplex SIC: hop between Radar TDD & Broadband Comms

✗ Why Beam Hopping (BH) Alone Fails
Fast μs beam switching breaks multi-ms coherent integration & echo reception

✓ Dynamic Service Hopping (Radar TDD + Comms)
Switch between a ~10 ms Radar TDD burst (1 5G frame) & Broadband Comms

Service-Hopping Cycle (e.g., T_hop = 100 ms): Radar TDD (~10 ms = 1 5G frame) + Broadband Comms (~90 ms)

① Radar TX Dwell	Guard	② Radar RX Dwell	③ Broadband Comms
$T_{TX} < \tau_{RTD}$ (~4–5 ms)	$\tau_{RTD} - T_{TX}$	$T_{RX} = T_{TX} + \Delta\tau_{disp}$	$T_{comm} \approx$ 85–90 ms (85–90% QoS)

■ 1. Echo RTD & Disp.

Sets $T_{TX} < \tau_{RTD}$ & T_{RX}

$T_{TX} < 2R/c$ = 4–6 ms

- Stop TX before echo arrives
- $T_{RX} = T_{TX} + \Delta\tau_{disp}$

■ 2. Vessel Velocity

↑ Pushes $T_{TX} \geq 5$ ms

$\Delta v = \lambda / (2 \cdot T_{TX})$

- 5 ms @ Ku (λ = 2.5 cm)
- Δv = 2.5 m/s maritime vessels

■ 3. Radar TDD Frame

1 5G frame without comms TX

$T_{radar} \approx$ 10 ms (TX + RX)

- Coherent ms integration gain
- Fine SAR → multistatic RX (B5)

■ 4. Cadence & QoS

Repeat every $T_{hop} \approx$ 100 ms

$\eta_{comm} \approx$ 85–90% (9/10 frames)

- 10 ms radar every 100 ms
- HARQ-safe + OISL sat stagger

Key Takeaways

01 MFSS Strategies — Geographical, multistatic (ISL sync) & day/night eclipse multiplexing on shared SatCom fleets

02 Waveforms & SSPA — CP-OFDM wins linear ISLR (flat spectrum); low-PAPR APSK DVB-S2(X) gains +2.4 dB with HPA back-off

03 IBFD & Massive Arrays — +45–54 dB integration relaxes ISAC SIC to 120–130 dB (vs. heavy 150–160 dB Comms) + D2D arrays

04 Service Hopping — 10 ms Radar TDD frame ($T_{TX} < \tau_{RTD}$, $T_{RX} = T_{TX} + \Delta\tau_{disp}$) every 100 ms retains 85–90% Comms QoS

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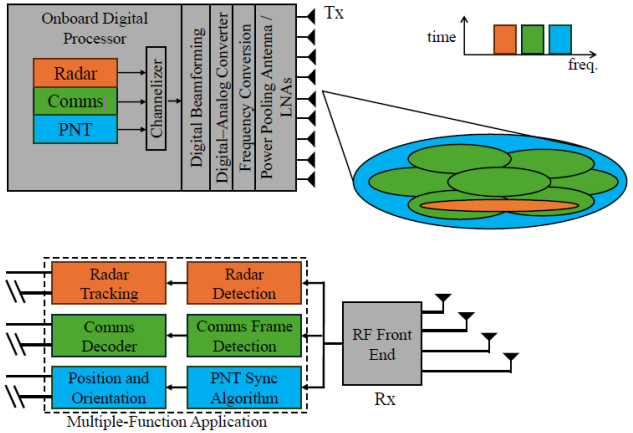
Appendix & Q&A

Backup Slides

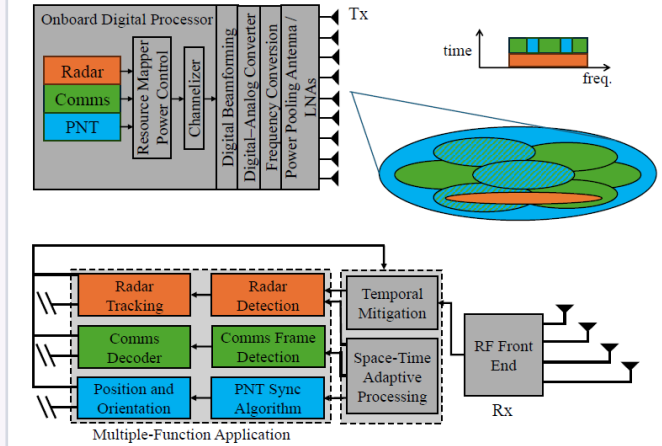
MFSS Taxonomy: Three Levels of Integration

1. Cooperative MFSS



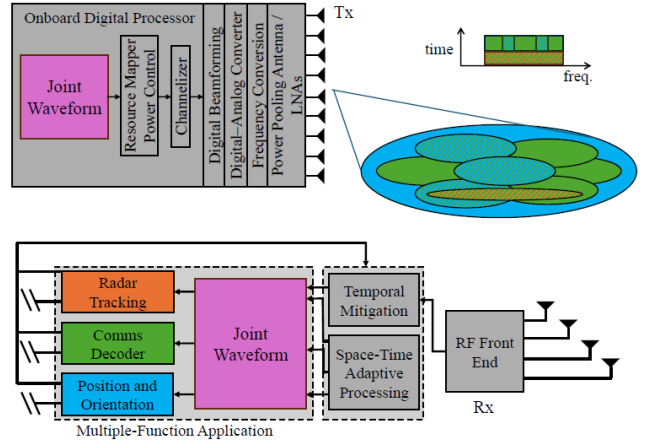
- Shared bus & power
- Separate RF & waveforms
- Disjoint resources

2. Integrated MFSS



- Shared SDR & aperture
- Dynamic grid scheduling
- Beam / Service Hopping

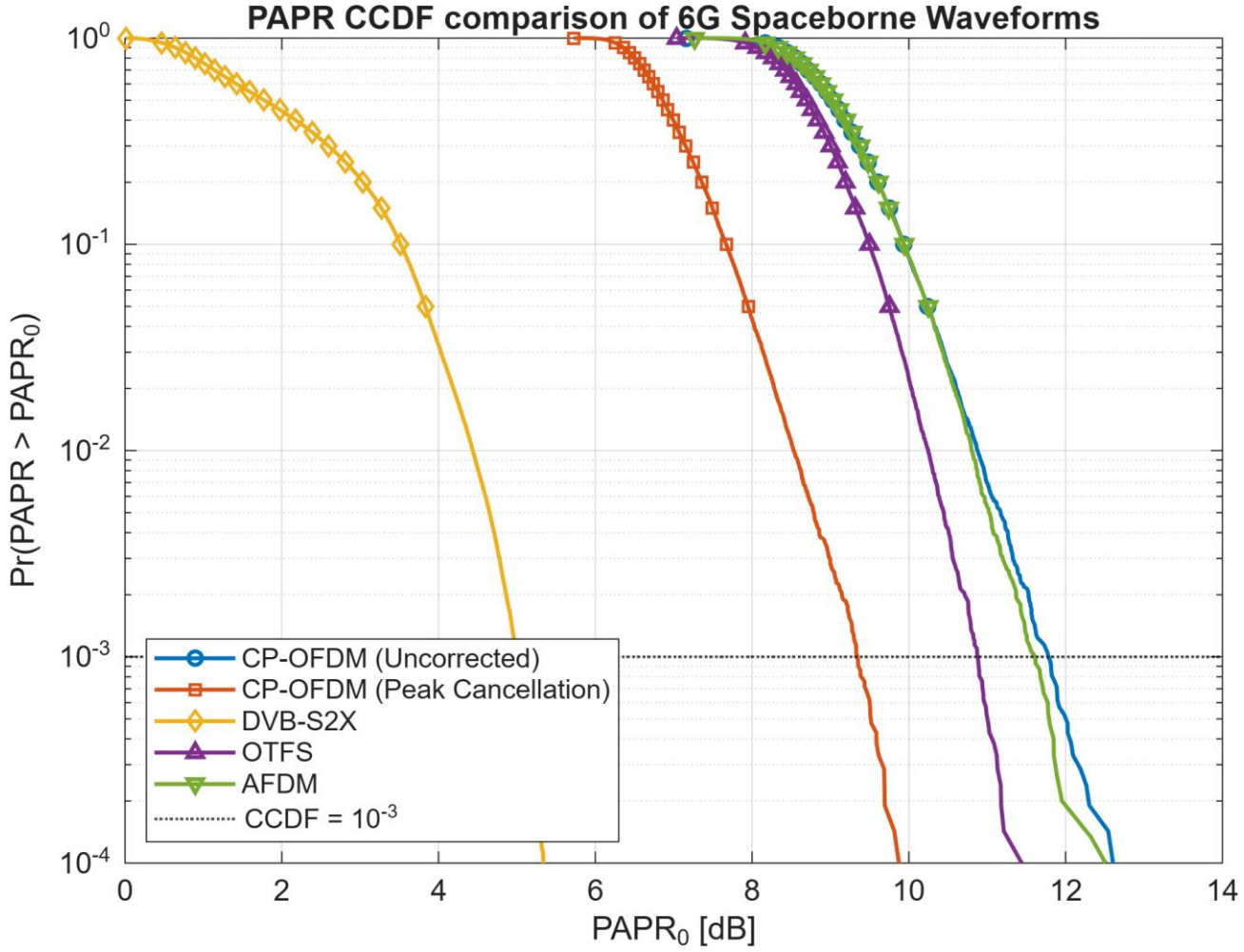
3. Joint MFSS (True JCAS)



- Unified dual-use waveform
- 100% spectrum & power reuse
- Requires IBFD / bistatic SIC

Waveform PAPR: OTFS N-Scaling vs. AFDM & DVB-S2(X)

OTFS Zak symmetry cancels M-subcarrier IFFT (depends on N); AFDM's N-IDAFT sums all N chirps (= OFDM)



■ DVB-S2(X) • 5.0–5.3 dB

- **Single-carrier time APSK (10^{-3} CCDF)**
- Low envelope variance + RRC shaping
- Beats CP-OFDM (11.8 dB) by ~6.5 dB

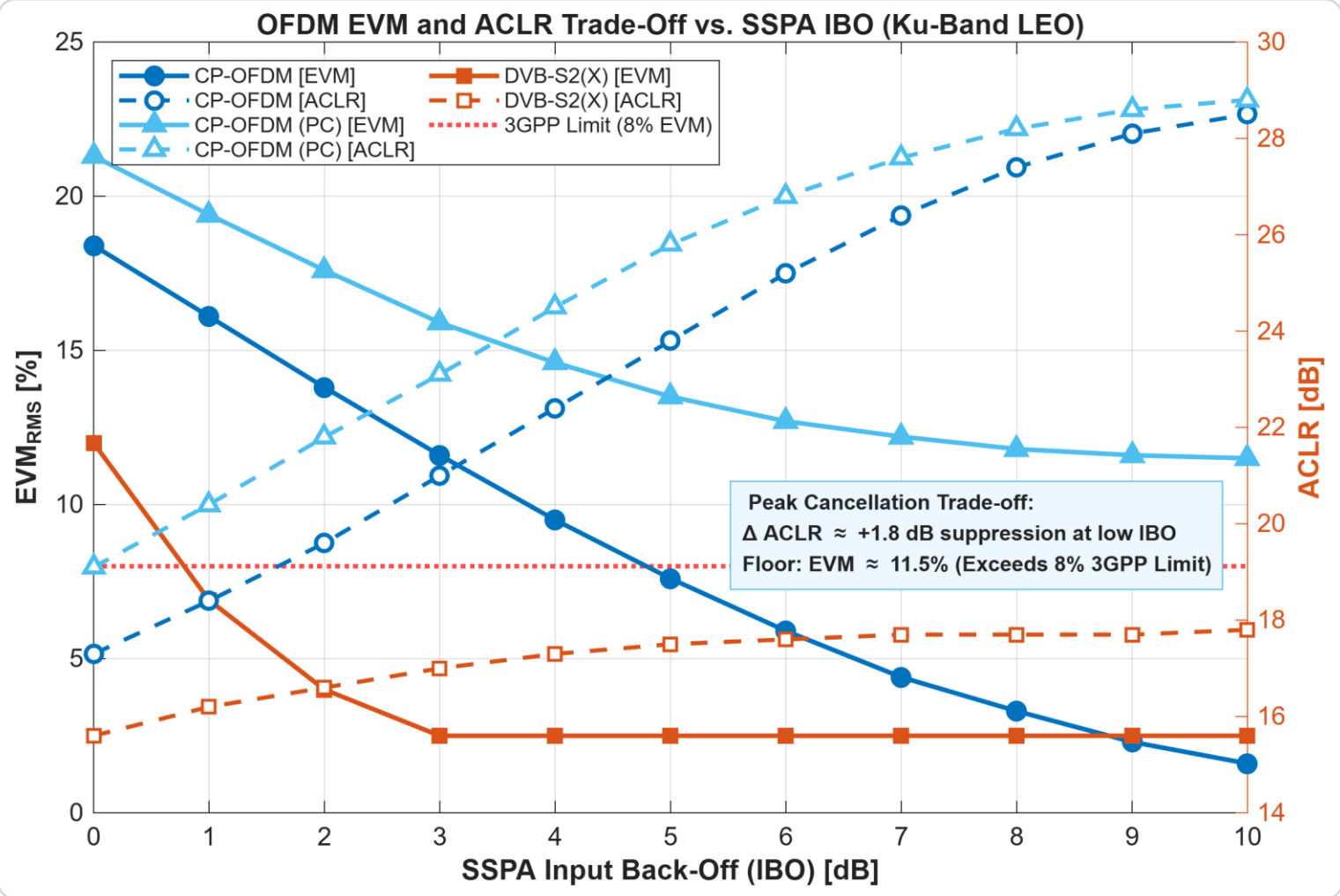
■ OTFS N-Scaling (10.9 dB @ N=14)

- **$F_M^H \cdot F_M$ cancels along delay (Zak)**
- N=1: 2.7 | N=4: 8.8 | N=14: 10.9 dB
- Radar $\Delta v = 1/(N \cdot T_{sym})$ forces $N \geq 14$

■ AFDM N-IDAFT (11.6 dB = OFDM)

- **$x = \Lambda_{c2} \cdot F_N^H \cdot \Lambda_{c1} \cdot s$ $(|\Lambda| = 1)$**
- Full N=2048-pt IFFT (no cancellation)
- Needs DFT-s precoding / DPD like OFDM

EVM & Spectral Regrowth vs. SSPA Back-Off



■ ACLR (Adj. Channel Leakage)

- **In-band / leaked adjacent power**
- Higher dB = less spectral regrowth

■ Peak Cancellation (PC)

- **Saves ~1.4 dB IBO (+1.8 dB ACLR)**
- Fails EVM: 11.5% floor (>8% limit)

■ Conclusion: DPD Required

- **Simple peak clipping breaks EVM**
- Multicarrier LEO needs onboard DPD