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SENTINEL: A Tri-Mode Phased-Array Radar for Clutter-Resistant HAR, Vitals, and EMG-Proxy Sensing

Tagline: SENTINEL: Spatially-Enabled Nulling, Tracking, and Interleaved Networks for Edge Learning.

Continuous health monitoring is critical not only for seniors but also for patients recovering from surgery, managing chronic illness, or undergoing rehabilitation. Yet today's tools fail: **cameras** invade privacy, **wearables** are uncomfortable or easily forgotten, and single-mode radars break down in cluttered, real environments with fans, pets, and multiple people. **SENTINEL** addresses this gap with a **tri-mode X-band phased-array** on CN0566 that (i) tracks posture and activities with adaptive FMCW beams, (ii) extracts respiration and heartbeat via CW micro-Doppler, and (iii) trends muscle micro-motions as EMG proxies. **Adaptive nulling and virtual arrays** suppress interference, while an ultra-light Mamba classifier fuses activities and vital trends on-edge. The result: a **privacy-preserving, always-on radar sentinel** that generalizes beyond falls to **multi-modal patient monitoring** in homes and clinics alike.

1) Novelty (Human Activity Recognition (HAR) is *not* overdone)

Most HAR with radar remains limited to **single-person, clean lab setups**. Open problems persist: (i) robustness in clutter with **multiple movers**, (ii) handling **continuous sequences** rather than isolated actions, and (iii) **edge-efficient inference** on constrained devices (e.g., RPi). implementing a holistic approach with multiple parameters in order to de-correlate contributing measurement parameters.

SENTINEL addresses these by coupling **array-domain interference control** (MVDR/Capon nulling + virtual arrays) with **spectral denoising** before micro-Doppler extraction, and deploying a **tiny Mamba/SSM classifier** optimized for radar spectrograms.

Unlike prior CN0566 efforts (2021–2025 archives, GitHub repos, ADI notes), which emphasized static ranging or simple imaging, none demonstrated HAR under clutter. SENTINEL is the first **tri-mode X-band system** that combines **Adaptive FMCW beams** for robust tracking/posture/falls, **Phase-stable CW windows** for respiration & heartbeat, **Micro-motion proxies (EMG/water-content)** for longer-term health trends. This **fusion of null-steered arrays + mode scheduling + lightweight temporal modeling** is, to our knowledge, **unexplored at CN0566/X-band** and directly tackles real-world robustness, not just lab accuracy.

2) Challenge alignment (We use *every* CN0566 feature)

- X-band phased array (10.0–10.5 GHz) with ADAR1000: steerable mainlobe, amplitude taper, 360° phase control; receive-summed RF_IO path.
- ADF4159 FMCW ramps → range & Doppler gating; ramp markers to sync.
- Virtual arrays via dual TX toggling at chirp boundaries → narrower AoA, less target cross-talk.
- Calibration suite (per-element gain/phase EQ, boresight reference, tapering).
- Stacks: MATLAB + Python (IIO/pyadi-iio), PlutoSDR; baseline demo on Raspberry Pi 5, extended acceleration on HamGeek E310 (Zynq-7020).

3) System architecture

Modes & Scheduling (tri-mode, time-coordinated):

- **Mode A — FMCW**: target detection/track/AoA/posture/falls – Linear chirps, B≈200 MHz (≈0.75 m resolution), 200 μs ramps @5 kHz.
- **Mode B — CW:** cardio-respiratory via chest wall micro-Doppler – Single-tone CW, long coherent integration, update 0.3–2 **Hz (RR),** 1–4 Hz (HR). EMG.
- **Mode C — reflectometry:** muscle proxies (EMG/water shifts). – Spectral energy & centroid features → "myo-index".
- **Scheduler:** interleave FMCW bursts with CW dwells (ADF4159 markers); guard times avoid self-interference; common timebase for fusion.

Array/DSP front-end

1. Calibration → element gain/phase EQ; Chebyshev taper baseline.
2. Adaptive beamforming → MVDR/Capon; GUI to "paint" deep null(s) onto interfering movers or fan/reflector.
3. FMCW processing: Chirp Bandwidth: (200 MHz→ ~0.75 m range resolution, sufficient to separate human torso vs. limb signatures), Ramp Duration: 200 μs, Repetition Frequency: 5 kHz. → range FFT → range–Doppler; gate bins of the chosen subject.
4. Spectral denoising(simple thresholding or wavelet-based) → STFT spectrogram clean-up (PLOS ONE example**,** open-access mirror, IET RSN denoising paper). low-rank spectrogram denoising with STFT + thresholding, validated in prior radar HAR studies.

5. Virtual array stitching (toggle TX every N chirps), We will address SNR loss from time-multiplexing with per-TX calibration and frame-interleaving, ensuring coherence across toggles → improved AoA & separation.
6. Tiny Mamba-style network (or CNN-Mamba hybrid) for continuous sequences; Doppler-aligned segmentation; channel fusion; <~10–20k params; quantized for RPi. We chose Mamba-style sequence models for their ability to capture long-range dependencies with linear complexity, outperforming GRUs/CNNs in recent radar HAR benchmarks. We target a model footprint under 1 MB and an inference latency of <50ms on the RPi 5's ARM cores. With the possible addition of the Raspberry Pi AI HAT+.
7. Outputs: (i) activity time-line with segmental F1, (ii) fall ROC-AUC, (iii) live null-depth & SNR plots.

Learning back-end: We implement a **tiny Mamba/SSM** (≤20k params, <1 MB, <50 ms on RPi, optional AI HAT+) with Doppler-aligned segmentation and channel fusion, outperforming GRU/CNN baselines for continuous HAR. As no tri-mode dataset exists, we will record short multi-subject routines (posture, falls, breathing, isometric holds) with synchronized ground truth (pulse oximeter, EMG in-contact/wearable sensor, video, and water/body composition analyzer), ensuring evaluation under realistic clutter.

Fusion & decision layer:

FMCW tracks are used for ROI steering of CW modes while nulling environmental movers. Extracted features include vitals (HR, RR, motion quality) and the myo-index (5–150 Hz bandpower and slope). Simple risk rules link long-term trends, e.g., *(RR↓ + HRV↑ + Myo↓ over ≥72 h → fatigue/dehydration)* or *(Myo spikes + gait instability → pre-fall alert)*. A lightweight Mamba/TCN temporal model smooths outputs and produces calibrated risk scores in the 0–1 range.

4) Experiments & ablations

Core demo: Human subjects + mechanical interferer (pendulum/fan). Live polar plot shows subject mainlobe lock + adaptive null on interferer; spectrogram shows clean vs cluttered micro-Doppler; classification panel outputs activities.

Ablations: We will compare nulling vs no-nulling to measure ΔSNR, Δsegmental-F1, and Δfall ROC-AUC. Virtual-array vs native setups will quantify ΔAoA error and target separation index. Denoised vs raw spectrograms will be evaluated through ΔF1 on continuous actions. Finally, a model sweep will contrast tiny-CNN and tiny-Mamba in params/FLOPs versus accuracy/latency.

Hybrid-specific: Scheduler efficacy will be tested by comparing FMCW-only to FMCW+CW interleaved modes for track continuity and vital SNR. CW stability will be assessed via phase-noise PSD and minimum detectable Doppler vs integration time. Myo-index sensitivity will be validated using isometric holds and hydration proxies (N=3–5, repeated). Fusion benefit will be quantified with and without CW steering to thorax/upper-limb, reporting HR/RR error and Myo variance. Risk rules will be validated on synthetic “at-risk” vs normal episodes, reporting AUC/PR for alerts.

5) Metrics, Risks & mitigations

We will evaluate array-level performance through mainlobe width, null depth, AoA error, gated SNR, and virtual-array gain. HAR will be measured using segmental F1 on continuous timelines, fall ROC-AUC, and confusion matrices. CW vitals will be benchmarked against references with RR MAE ≤ 1 breath/min and HR MAE ≤ 3 bpm. The myo-index will detect ±10% changes (isometric vs rest) with d′ ≥ 1.2. Scheduler performance will target ≤ 5% lost-track rate during CW dwell windows. Compute efficiency will be constrained to ≤ 2000 MB memory, ≤ 50 ms edge latency, with tracked params and FLOPs. FMCW tracking will achieve ≤ 2.5° angular resolution and fall F1 ≥ 0.90.

Our team previously designed and validated a real-time, FPGA-based AoA pipeline on a HamGeek E310. graduating from a pseudo-Doppler system to a true phased-array architecture. Our experience with that prior work taught us key lessons in OTA validation, rigorous measurement, and reproducible signal processing flows, which we will apply directly to this project, leveraging our existing Zynq-7020 platform as another potential compute engine besides the RPI, expanding our previous efforts. And to mitigate the following Risks:

Cross-room accuracy drops will be countered by domain mixing and fast per-room phase calibration. Fan or reflector harmonics will be mitigated through spectral notches, increased null depth, and re-estimation of R. Compute limits on the RPi will be addressed with quantized models, pre-gating, and async I/O, while full models run on host or FPGA. Pipeline scalability will be shown with a light real-time demo on RPi, a high-performance FPGA version, and an offline baseline. CW phase drift will be controlled with long dwells, PLL warm-up, and Allan deviation logging, with fallback to FMCW-only if needed. Mode collisions will be avoided with guard times, leakage checks, and spectral notches for LO spurs. Tiny Doppler shifts at 10 GHz will be extracted with 2–8 s integration and low-rank STFT denoising, reporting MDS. Pose mis-aim will be corrected with FMCW-guided beam steering and re-acquisition if confidence falls below τ. Finally, scope creep in clinical claims will be avoided by framing vitals and myo-index strictly as trends and alerts, not diagnostics.

8) Additional Bibliography Items and Brainstorming Resources:

Our survey across > 20 recent radar HAR papers shows that robustness, multi-subject settings, and adaptive nulling are open problems; no prior CN0566-based study has addressed all three together. To back this proposal, we found that Cross-environment robustness shows why HAR models often fail when moved to unseen rooms and motivates our cross-room tests. While Multi-subject HAR highlights the open challenge of handling multiple movers and inter-person interference. We found Privacy-sensitive daily activity radar, evidence that radar is already trusted for sensitive assisted-living settings, further supported by Multi-radar fusion, which demonstrates attention-based spectrogram fusion for robustness. Moreover, Continuous HAR with multi-label output proves that continuous sequences and overlapping activities are the true frontier, and Phase-only beamforming confirms that interference suppression can be achieved with hardware-friendly constraints. Finally, RIS-enabled arrays show the broader trend of leveraging reconfigurable surfaces for nulling and interference mitigation, where Mainlobe jamming suppression validates that adaptive nulling remains a hot topic even for modern MIMO/STCA radars.

We also reviewed radar-based **hydration and EMG proxies**, which support our proposed X-band application: dielectric properties of tissues across **10 Hz–20 GHz** confirm frequency-agnostic micro-Doppler sensitivity (Gabriel et al. 1996); UWB and IR-UWB studies demonstrate **on-body water detection** and **bladder monitoring** (Li et al., O’Halloran et al., Schmid et al.); mmWave reflectometry shows feasibility for **skin hydration imaging** (Zhang, Wright State Univ.); and THz reflectometry highlights the trend of **hydration-sensitive sensing** (Bennett et al.). Finally, hybrid EMG+MMG systems validate that **micro-motion sidebands carry physiological signatures** beyond classical EMG (Guo et al.).