HF data modems and an improved adaptive hybrid

Version 3 / 17 November 2026

An integrated review of xara, Aether HF, Data2G, Mercury v2 and Ion HF, followed by a proposed adaptive HF modem architecture.

Recommendation: combine mature channel estimation and error recovery with a bounded receiver and an explicit HARQ/control contract. Select guard, pilot density and waveform family using uncertainty and delivered goodput. Add low-order DFT spreading or a bounded time-varying equalizer only when paired measurements justify their cost. Preserve a robust fallback rather than treating long-guard OFDM as the answer to every severe channel.

Design	Principal strength to study	Important boundary
xara	Efficient PSK/QAM and a VARA radio-compatibility target	Its inspected channel correction is not a full Doppler-ICI receiver
Aether HF	Frequent pilots, HARQ and explicit transmission grants	Pilots track variation; they do not remove all within-symbol ICI
Data2G	Rich constellations, 2-D estimation, decoder-aided refinement and mode prediction	A source of receiver and link-layer techniques, including a separate CPM fallback
Mercury v2	Receiver-driven outer erasure repair	Fresh repair pieces and PHY retransmissions have different identities
Ion HF	Channel-informed waveform families, low-order spreading and a guarded MFSK floor	Its strongest severe-channel evidence is low-rate frame delivery, not fast OFDM
Proposed hybrid	A bounded receiver/model bank and an end-to-end adaptation contract	Architecture hypothesis; no matched-channel superiority demonstrated

Evidence labels. Source: analysis of the identified modem snapshots. Calculated: arithmetic from stated parameters. Published: project-reported results, not reproduced here. Proposed: a design/test candidate, not an implemented or validated feature.

The source register identifies the reviewed revisions. Ion is pinned at `1eb7dca01803e120eeb0924fd02d4ccc563557a4` (2 November 2026). Every hybrid block, waveform choice and evaluation gate in this document is a proposal. The numerical evidence concerns the compared modems, not a demonstrated hybrid. [X1, A1, D1, M1, I1]

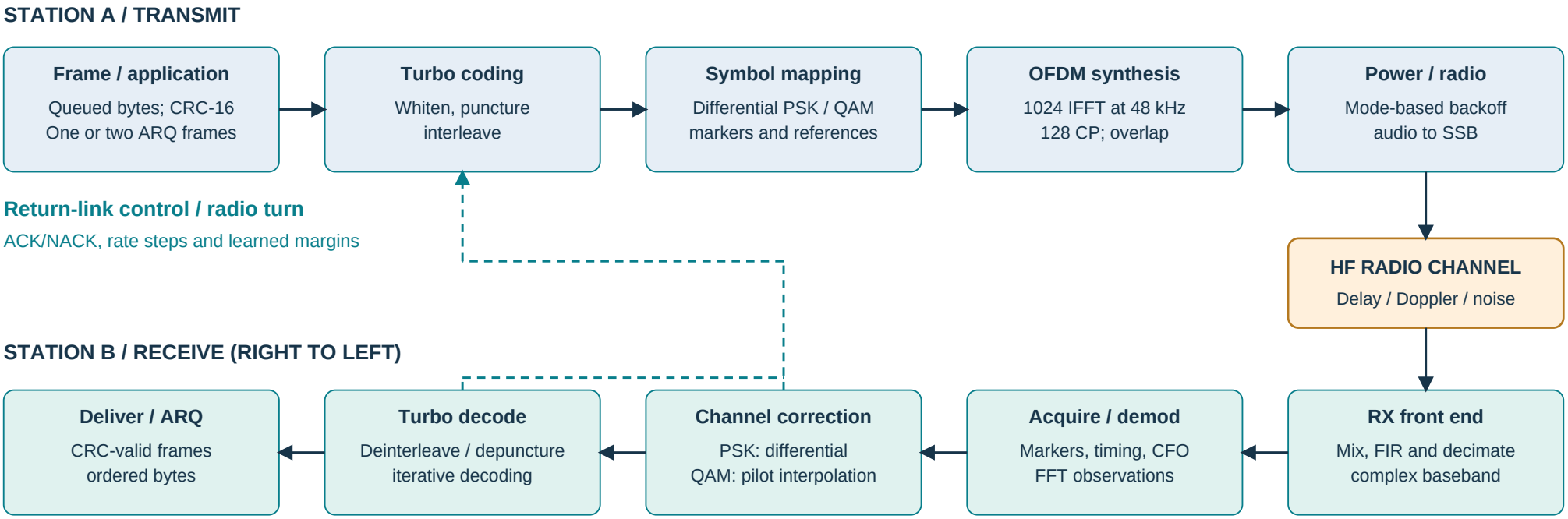
1. Physical and link-layer comparison

Design	Grid and training	Receiver, recovery and transmit power
xara	59 carriers / 2750 Hz; 46.875 Hz spacing; 21.33 ms useful + 2.67 ms prefix; QAM references every 192 ms per carrier	Differential PSK or pilot-corrected QAM; turbo-coded ARQ without retry soft combining in the inspected path; mode-based power backoff
Aether HF	57 carriers / 2300 Hz, including 15 comb pilots; 40 Hz; 25 ms useful + 6 ms nominal prefix (5 ms effective); comb observations each 31 ms	Motion-dependent pilot smoothing and noise weighting; LDPC/HARQ-IR, selective repeat and grants; clip/filter TX
Data2G	48 carriers / 2400 Hz; 50 Hz; 20 ms useful + 4 ms prefix; full pilot every 144 ms plus closing pilot	Delay/Doppler-aware 2-D estimation and soft refinement; LDPC/HARQ and learned outcome prediction; clip/filter and constellation extension
Mercury v2	33 carriers / about 2100 Hz; 62.5 Hz; 16 ms useful + 4 ms prefix; full pilot each 100 ms	Pilot/clock tracking; LDPC inside a Reed-Solomon repair carousel; clipped QPSK, top QAM mode unclipped
Ion HF	Normal: 49 carriers / 2450 Hz, 50 Hz, 20 + 4 ms. Long: 97 / 2425 Hz, 25 Hz, 40 + 10 ms. Also 650 Hz slices and 32-tone MFSK	Scattered-pilot Wiener estimation, error-aware LLRs and bounded refinement; LDPC/HARQ, channel reports and goodput selection; DFT-spread QPSK/8PSK, plain 16/64QAM

All five expose VARA-style application interfaces. This says nothing by itself about radio interoperability: Ion, Aether, Data2G and Mercury have their own air protocols. xara's VARA-radio target is a distinct requirement. [X1, A1, D1, M1, I1-I3]

Proposed adaptation policy. Guard length, pilot density, constellation and code rate are separate decisions. First rule out a waveform the channel cannot support; then optimize complete-exchange goodput among the remaining negotiated choices. Track uncertainty and switching cost. A failed high-SNR waveform should not be rediscovered by losing a burst at each of its faster modes.

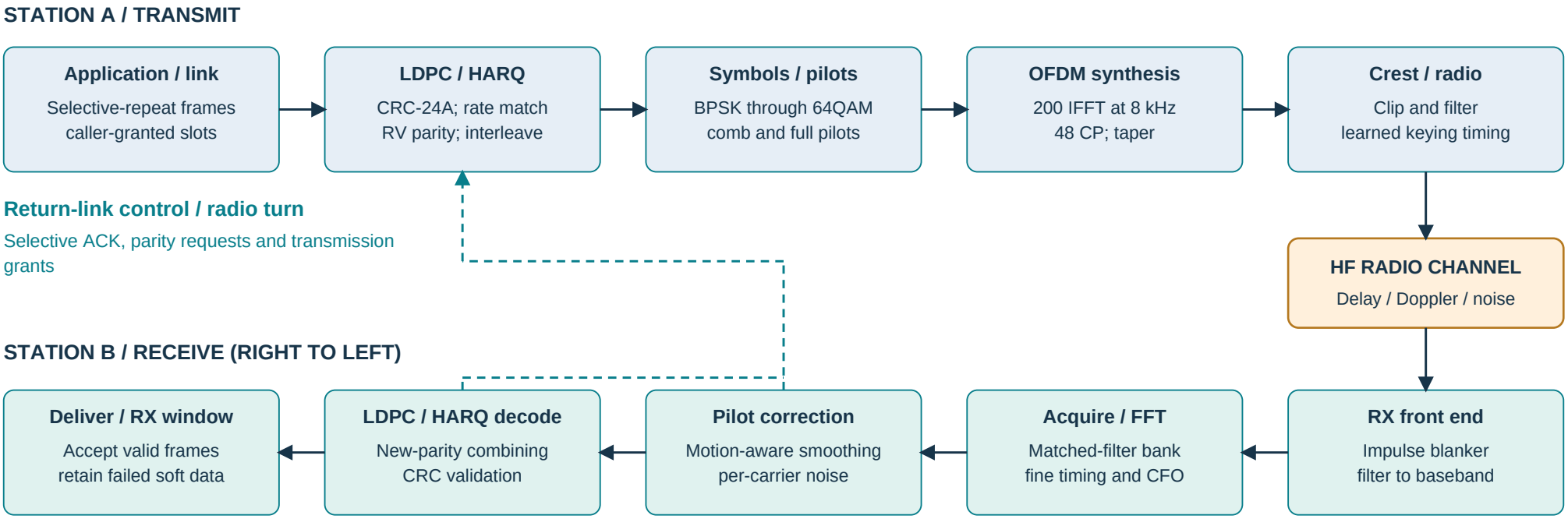
2. Signal-chain atlas: xara



The diagram shows the inspected OFDM path. Lower levels use FSK or a few pulse-shaped parallel PSK carriers and bypass OFDM synthesis. QAM uses pilot interpolation; lower-order OFDM detects phase differences. The turbo decoder iterates internally, but the inspected ARQ does not retain soft information across retries. [X1]

Lesson for the hybrid: preserve a clear distinction between internal decoder iterations, channel refinement and combining retransmissions. Compatibility targets belong in the host/backend contract, not in an assumption that a shared command syntax implies a shared radio waveform.

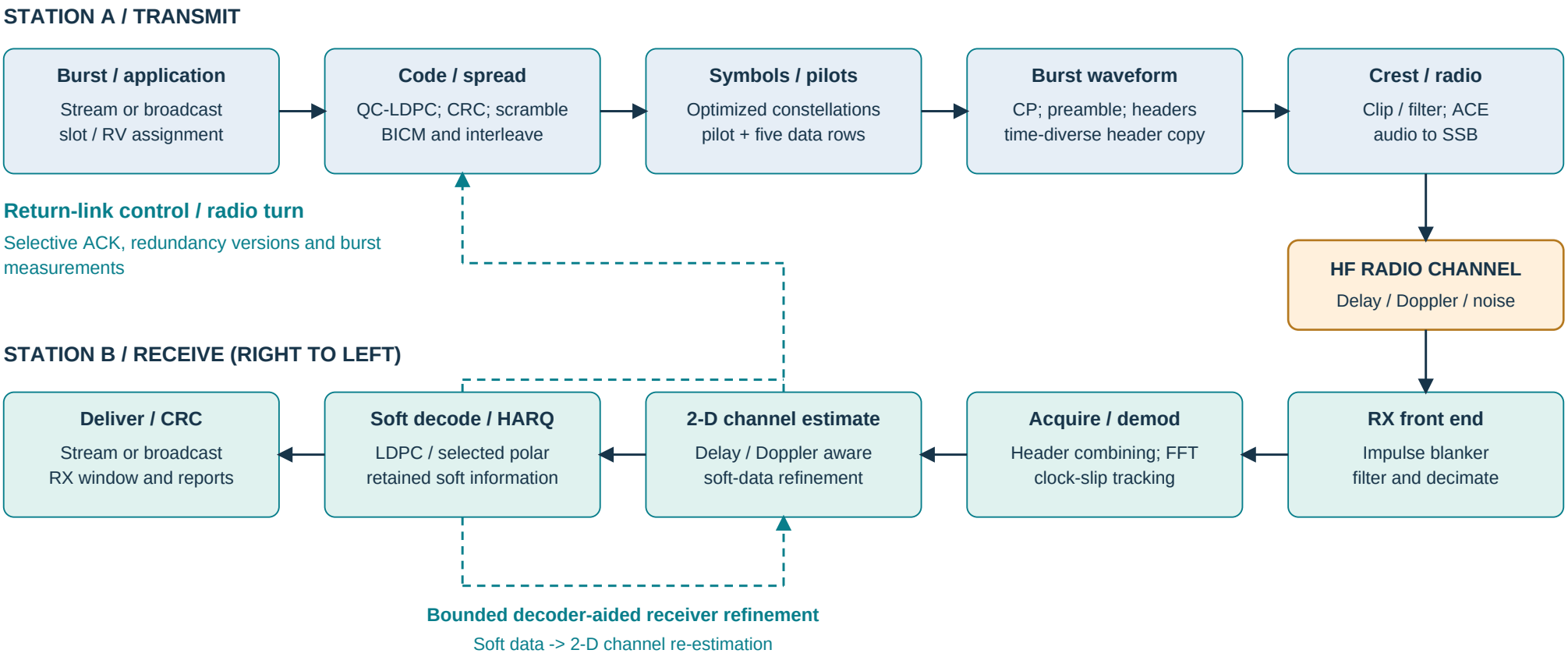
3. Signal-chain atlas: Aether HF



The OFDM chain combines comb and full pilots with motion-dependent smoothing; separate continuous-phase FSK tone modes cover weak paths. Selective-repeat framing and redundancy versions preserve failed codewords for incremental parity. The caller grants transmission slots; rate and keying-time decisions include delivery and turnaround costs. The inspected equalizer does not model all cross-carrier Doppler ICI. [A1-A3]

Lesson for the hybrid: pilot timing and explicit turnaround ownership are as important as constellation order. Aether fixes scheduling authority at the caller: the other station transmits only in a time-bounded grant, and a response that cannot start on time is forfeited. Evaluate this policy against conventional turn-taking under lost control and late decoding. [A4]

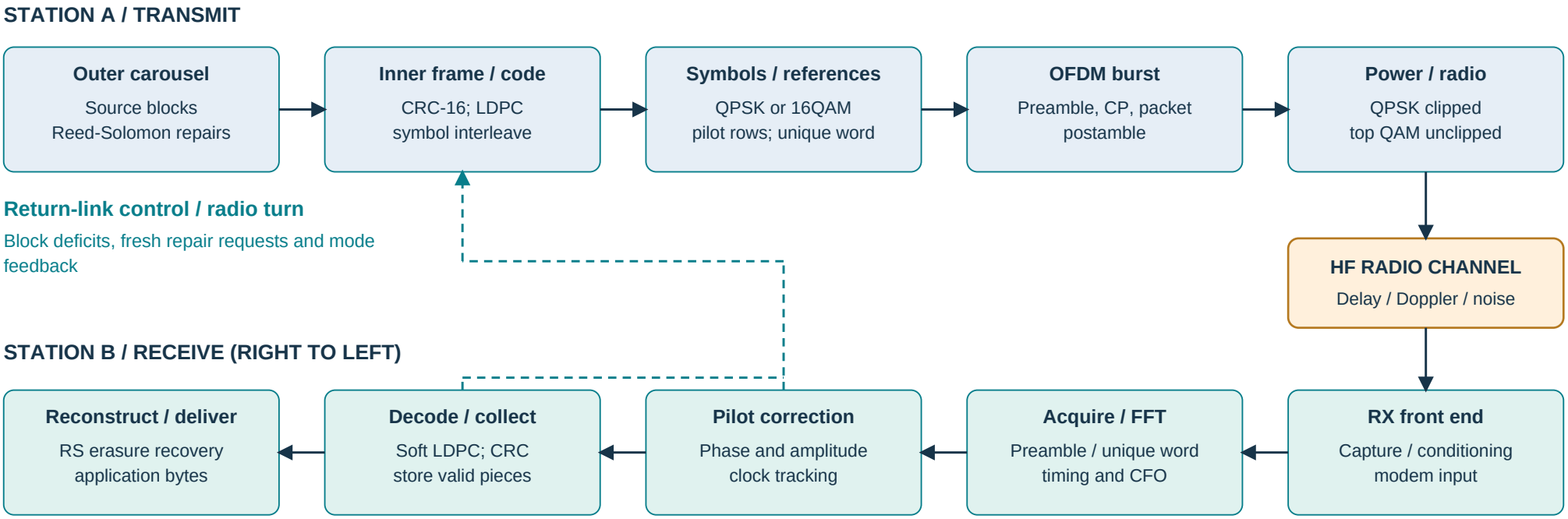
4. Signal-chain atlas: Data2G



QC-LDPC serves the top OFDM modes; selected robust/control modes use polar codes, while separate CPM data modes use nonbinary GF(M) LDPC. The burst contains time-diverse header information. Soft decoder output can become uncertain reference data for 2-D channel re-estimation; LDPC retries use incremental redundancy, while polar retries use Chase combining. A learned outcome predictor selects mode and burst duration. [D1-D3]

Lesson for the hybrid: adopt mature estimation, clock tracking, uncertainty-aware refinement and rate prediction before adding a more ambitious receiver. Actual pilot locations and waveform timing must enter those models. Neither ordinary refinement nor CFO correction alone is a general within-symbol ICI equalizer. [D1-D3]

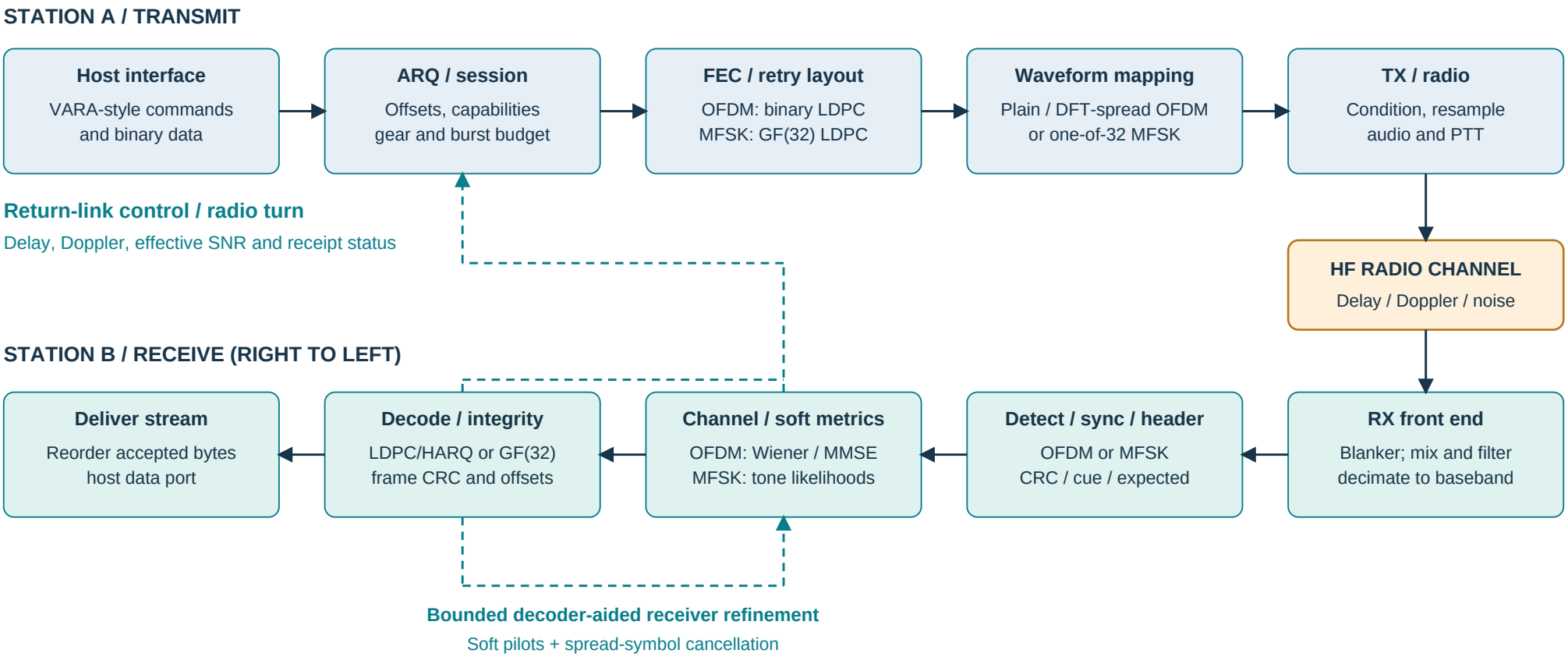
5. Signal-chain atlas: Mercury v2



The carousel transmits new Reed-Solomon repair pieces, each protected by an inner CRC/LDPC frame. The receiver collects valid pieces and requests more according to remaining block deficits. Fresh pieces are different inner codewords; the carousel therefore disables Chase soft combining. A separate 32-MFSK floor supports fringe operation. [M1-M3]

Lesson for the hybrid: inner HARQ and outer erasure repair solve different losses. Mixing their identities can silently corrupt combining state. Outer repair is a later option for broadcast or a demonstrated turnaround bottleneck; it should not delay a correct, bounded connection with selective-repeat ARQ and stable soft-combining identities.

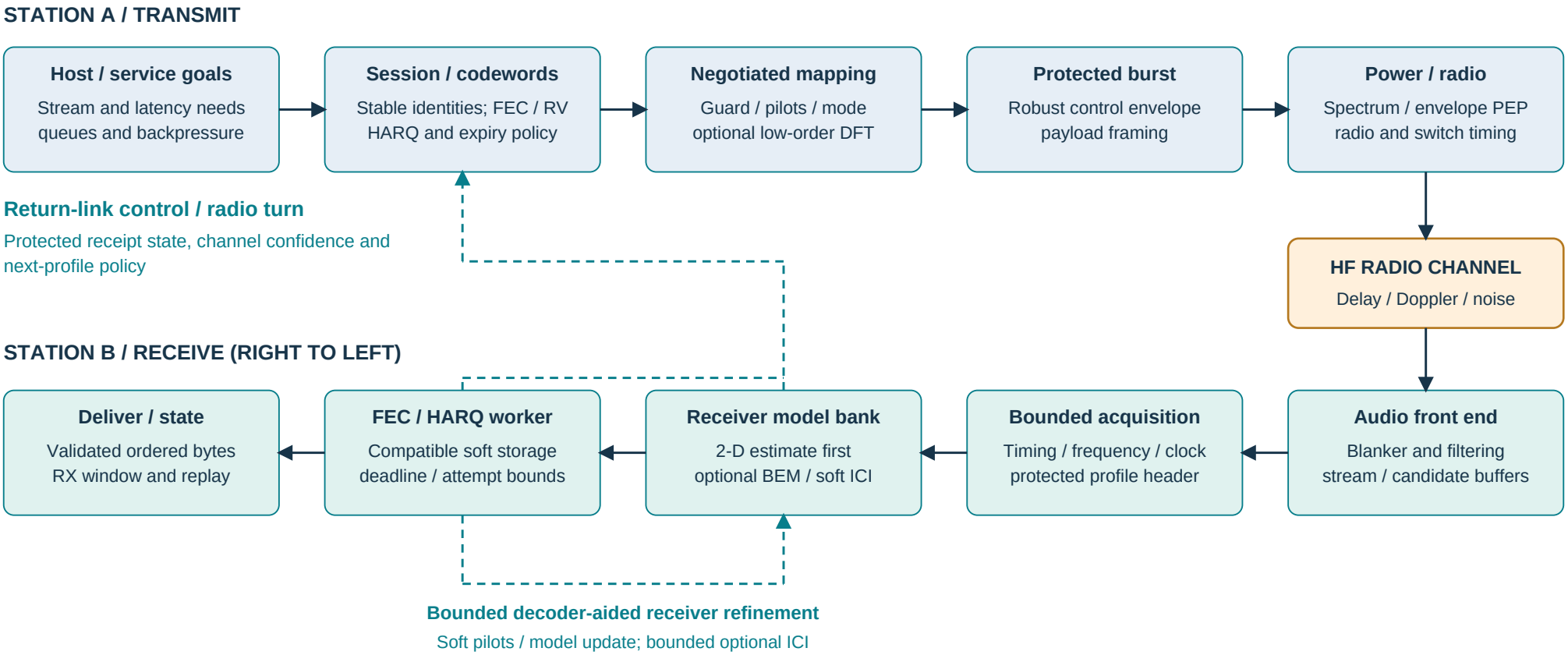
6. Signal-chain atlas: Ion HF



Ion's 17-level ladder moves between MFSK, a narrow OFDM slice, long guard and full band. OFDM uses binary rate-compatible LDPC/HARQ; MFSK uses GF(32) tone likelihoods and bypasses the OFDM equalizer. QPSK/8PSK use DFT spreading; 16/64QAM remain plain because its spread settings lose on fading. The lower loop refines soft pilots and cancels spread-symbol interference, not arbitrary Doppler ICI. [I2-I6]

The dashed ACK path is a separate radio turn, carrying receipt state and channel reports. A negotiated MFSK cue can protect weak OFDM timing/layout at roughly 1.12 s extra airtime. **Lesson:** measure acquisition/control survival, family selection and equal-peak power together. Spreading alone is not the whole low-PAPR improvement. [I3, I6]

7. Improved hybrid architecture

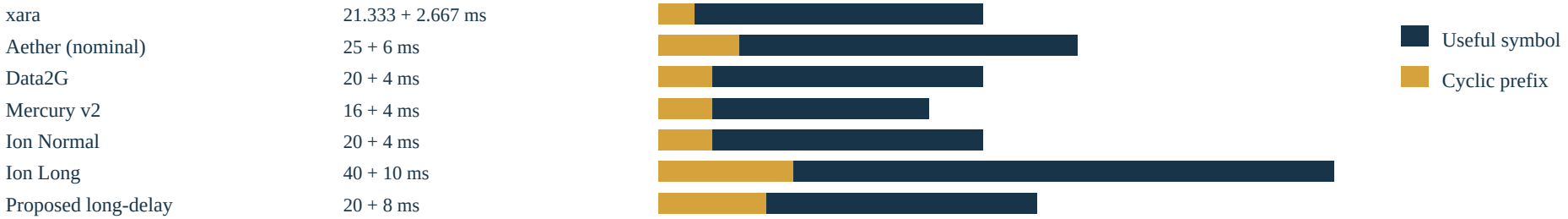


Proposed architecture. Separate host flow control, session state, coding, waveform generation and radio timing. Separate the control envelope from the negotiated payload profile, and preserve stable codeword identities beneath changing packet layouts. The receiver uses a small model bank: ordinary 2-D estimation first; bounded time-varying equalization only when residuals and uncertainty justify it.

A policy layer combines channel reports, observed delivery and measured CPU/turnaround cost to choose profile, pilots, mode, redundancy and burst length. A profile is admitted only after its acquisition, control, spectrum and deadline gates pass. Optional DFT spreading is limited first to low-order modes. Evaluate a constant-envelope fallback alongside the OFDM choices: Data2G's CPM and Ion's guarded MFSK illustrate different coding, acquisition and power tradeoffs. [D1-D3, I2-I7]

8. Guards, pilots and waveform families

NOMINAL SYMBOL TIMING / COMMON TIME SCALE



Pilot overhead is separate from prefix overhead; acquisition and taper details omitted.

Proposed operating family	Guard / useful time; pilot decision	Design rationale and admission rule
Quiet path	About 2.5-4 / 20 ms, 50 Hz spacing; sparse training only when justified	Lower overhead must survive timing error, radio filtering and channel drift
General fading	About 4 / 20 ms, 50 Hz spacing; adaptive full/comb references	Use held-out prediction and control survival to set training density
Long-delay NVIS	About 8-10 / 20-40 ms, 50-25 Hz spacing; delay-aware references	Longer symbols pay for the guard but increase Doppler sensitivity
Fast variation	About 4-8 / 10 ms, 100 Hz spacing; denser training	Shorter symbols and optional ICI processing; prove channel identifiability and CPU limits
Constant-envelope fallback	Guarded MFSK or CPM, with its own robust control design	Admit only after acquired data and reverse-link control tests; allow explicit outage

Ion's Long pilot grid is 75 Hz by 200 ms; Normal is 150 Hz by 96 ms. Long handles delay economically but becomes marginal in Ion's 7 ms / 2 Hz study. Its link excludes OFDM above a measured 6 Hz Doppler class. These are Ion-specific findings, not universal selector constants. Changing a guard never proves that the preamble or bootstrap works through the same echo. [I2, I3]

9. Receiver, control and HARQ contract

Bounded reception. Separate streaming detection from worker-side decoding. Keep searching while a candidate is pending; a false header must not hide the next real burst. Bound retained audio, candidate count, packet size, soft storage and computation. Validate arbitrary chunking, long noise runs, malformed lengths, late packets and clock drift.

Uncertainty before complexity. Use a 2-D estimator parameterized by actual pilot times. Include thermal/local residual noise and channel-error variance in soft metrics. Ion's held-out-pilot model choice and conservative residual calibration are useful checks against confident errors. Apply soft-data refinement without counting a cell's own sample as independent evidence. [D3, I6]

Optional time variation. Model delayed paths over the useful symbol with a small basis expansion; estimate a banded frequency-domain channel and use bounded MMSE/soft cancellation. Cap model order, coupling width and iteration count by a measured deadline. Reject optimistic model fits; revert to the simpler receiver or fallback when evidence is weak. Ion's spread-symbol cancellation is not proof of this Doppler receiver. [T1]

Protect the complete control loop. Measure acquisition, headers, ACKs, fallback and resynchronization floors separately from payload FEC. Add a robust cue only if the header is the bottleneck. State-aided expected headers need bounded candidate lists, likelihood margins, false-accept tests and all epoch/direction/canonical checks. Do not guess unsolicited turn/disconnect transitions. [I2, I3]

Stable repair identity. Specify an epoch, direction, stable codeword or byte-range identity, coding family and redundancy span. Packet sequence is for replay control, not the codeword's combining identity. Bind the protected metadata to each payload; combine only compatible codeword positions and normalize soft information consistently. A packet-layout change must not silently change the protected codeword being combined. Bind codeword integrity to stable identity and signal layout/redundancy metadata explicitly. Bound retries and expiry; never combine outer repair pieces as if they were the same inner codeword. [M3, I3]

10. Rate, bandwidth and power accounting

Design	Data-portion figure	What the figure does not establish
xara / 2750 Hz	8.485 kbit/s PHY payload; about 8.218 with one-frame acquisition/framing	Excludes ACK, switching, retries and remaining link bytes
Aether / 2300 Hz	5.903 kbit/s PHY payload; about 5.551 per framed burst	Excludes full exchange timing, link bytes and filter flushing
Data2G / 2400 Hz	8.222 kbit/s PHY payload; 3.116 at one codeword, 8.017 at PHY maximum	Normal ARQ is shorter than the 64-codeword PHY maximum
Mercury v2 / about 2100 Hz	3.130 kbit/s PHY payload; about 2.941 with pre/postamble	Carousel, silence/gaps, polls and repair still cost airtime
Ion Normal / 2450 Hz grid	Calculated 9.167 kbit/s information: 44 x 6 x (5/6) / 0.024	Before frame CRC, preamble, header, ACK and retries; not a payload benchmark

Historical payload figures above retain the reviewed source conditions; Ion's row is explicitly a different, pre-CRC resource calculation. None is a matched application-goodput ranking. Nominal carrier span, filter passband and measured occupied bandwidth are separate: Ion reports about 2580-2610 Hz occupied for its nominal 2450 Hz layout. Verify spectrum after all final TX processing and map host bandwidth commands to qualified profiles. [X1, A1, D1, M1, I2]

For a design calculation, assume 48 active carriers, QPSK rate 1/2 and one sixth of cells reserved for pilots. A 20 ms useful symbol with a 4 ms prefix yields about 1667 information bit/s; an 8 ms prefix yields 1429: `R = carriers x (1 - pilot_fraction) x bits_per_cell x code_rate / symbol_seconds`. CRC, padding, acquisition and link traffic reduce finite-packet delivery. These are illustrative resource budgets, not defined operating modes or goodput forecasts; success and exchange efficiency must be measured.

Equal mean power and equal peak power answer different questions. Ion reports about 1.8-2.1 dB AWGN QPSK improvement at equal peak for a combined spreading/gain/clipping mode; its higher-order spread modes lose on fading. Compare complete bursts, including preamble and ACK drive, under both normalizations. A digital real-sample peak limit is not RF PEP calibration or envelope crest reduction. [I2, I6]

11. Severe-channel comparison

Design	NVIS: 7 ms / 1 Hz	Low latitude: 6 ms / 10 Hz	High latitude: 3 ms / 10 Hz; 7 ms / 30 Hz
xara	OFDM guard exceeded; fallback/outage evidence incomplete	Guard and ICI stress; no matched goodput estimate	Fast variation; extreme also exceeds guard; no defensible common-condition rate
Aether HF	Effective guard exceeded; published low-rate scenario exists	Frequent pilots help tracking; delay/ICI remain	3 ms nominally fits guard; published polar scenario exists. Extreme exceeds guard and stresses tracking
Data2G	Nominal OFDM guard exceeded; CPM is a separate path	2-D refinement does not remove all ICI or extend CP	3 ms fits nominal CP; extreme exceeds it. Matching application rates unavailable
Mercury v2	Guard exceeded; separate MFSK floor	Guard/acquisition/tracking stressed	3 ms fits nominal CP; extreme stresses guard and tracking; matched rates unavailable
Ion HF	Long OFDM and guarded MFSK are purpose-built options	Author reports MFSK success; OFDM does not cover this fast fading	No matching 3 ms / 10 Hz table in this review. At 7 ms / 30 Hz, R0 data reaches about 90% near -9 dB mean SNR2.4k
Proposed hybrid	Validate long-guard acquisition, timing and pilot design	Compare fast-symbol/ICI options with constant-envelope fallback, including control	No validated forecast. At 7 ms / 30 Hz, prioritize robust degraded service or explicit outage

The selected ITU profiles specify delay and Gaussian frequency spread (conventionally 2 sigma), not received SNR or throughput. A guard shorter than the delay is a failure mechanism, not proof of zero delivery; a long guard is likewise not proof of acquisition or decoding. [T2]

Ion's R0 uses a 20 ms tone window plus 8 ms guard and GF(32) LDPC. Its reported severe-channel 90% points are approximately -10 dB for NVIS, -11 dB for 6 ms / 10 Hz and -9 dB for 7 ms / 30 Hz, in mean SNR over 2.4 kHz. Those are acquired one-frame tests, roughly 8 s per burst, not two-way session goodput. They establish a useful fallback comparator, not a claim that OFDM wins the extreme channels. [I4, I5]

12. Numerical evidence and a fair campaign

Keep unlike evidence unlike. Published Aether scenarios from baseline build `3e272ad`: about 31.2 bit/s on its NVIS/500 Hz scenario at +8 dB SNR3k, and 129.8 bit/s aggregate on its polar/2300 Hz scenario at +12 dB, including different lifecycle/direction costs. Data2G publishes about 3409 bit/s on MPP at 20 dB PEP/noise3k. None fills all severe-channel cells. [A3, D4]

Ion reports about 7.42 kbit/s on WGN and 6.38 on MPP at +30 dB of its peak-referenced 3 kHz IONOS scale, over ten-minute software ARQ sessions, compression off, two seeds per cell. Its published Winlink comparisons have different host, hardware, bandwidth and turnaround overhead. Its Mercury benchmark uses **Mercury 1.9.21**, one seed per cell, not the v2 carousel reviewed here. These results are promising but cannot rank this proposed architecture. Pin exact feature flags: Ion's defaults evolved beyond some published tables. [I11, I12]

Proposed comparative evaluation:

- Pin every implementation revision, build flags, channel code and per-direction fading seeds. Save raw per-seed traces; first validate channel power and delay definitions against known cases. IONOS calibration is not interchangeable with an arbitrary simulator carrying the same profile name.

- Sweep AWGN, 2 ms / 1 Hz, 7 ms / 1 Hz, 6 ms / 10 Hz, 3 ms / 10 Hz and 7 ms / 30 Hz. Declare CFO/clock drift, filtering, interference and nonlinear distortion separately. Use enough seeds to report uncertainty.

- First measure acquired frame and control success. For complete modems, measure connect-to-last-byte goodput, tail latency, outage/recovery and exact byte delivery for short and long incompressible transfers, including asymmetric return paths and lost ACKs.

- Report equal-average and equal-peak results separately, occupied spectrum, worker deadlines, peak memory and CPU on the same host. Use paired ablations for estimator, guard/pilots, selector, cue, spreading and ICI.

No new modem/channel benchmark was executed for this review. Establish correctness before paired performance experiments; neither published tables nor proposed architecture diagrams demonstrate hybrid performance. [I11, T2]

13. Evaluation sequence and decision gates

Stage	Candidate capability	Required evidence
1	Bounded streaming receiver with noise and clock estimation	Chunk independence, false-lock recovery, malformed-input bounds, reference/optimized agreement and decode deadlines
2	Stable codeword/RV metadata, ARQ and host interface	Lost/reordered control, asymmetric links, replay, reset, backpressure and exact stream recovery across rate/profile changes
3	Channel/error reporting and constrained profile selection	Calibrated metrics, stale-report tests and paired goodput gains without profile flapping or repeated dead-family probes
4	Qualified constant-envelope fallback and optional low-rate control cue	Acquisition/ACK survive intended channels; negotiation and complete-exchange gains justify overhead
5	Low-order DFT-spread experiment	Same spectrum and peak constraints; reference/optimized agreement and acquired link benefit after distortion/deadline costs
6	Optional fast-symbol or BEM/ICI model	Held-out prediction, bounded CPU/memory and repeatable gain over the simpler receiver/fallback on declared channels
Later	Lifeline-style hold/resume; optional outer repair	A measured outage or turnaround problem; bounded queues, host abort semantics, stream integrity and clear break-even rules

The ordering is deliberate: establish trustworthy control, soft information and repair identity before adding a more ambitious equalizer. Ion's Lifeline retains queued/acknowledged offsets while discarding stale HARQ soft state and uses bounded probes/hysteresis. Its outer repair stream is useful only beyond measured transfer-size/goodput thresholds. Adopt those policies only when the corresponding bottleneck is demonstrated. [I3, I9, I10]

Modularity and attribution. Define narrow interfaces for waveform generation, channel estimation, FEC and session policy. Keep a transparent reference model and reproducible vectors alongside optimized processing. Methods can be evaluated without combining whole modem codebases. Preserve applicable licenses and notices when reusing code. Credit **Ion HF by Jesse Forkum, N0JLF**; its pinned revision is Apache-2.0, while releases through alpha.4 retain GPL-3.0-or-later. Its IONOS port has separate ARSFI/MIT attribution. No Ion source was imported for this review. [I1, I14]

14. Source register and reproducibility

Review date: 17 November 2026. Historical comparisons use the identified source snapshots, not synchronized current releases. Ion methods were checked against selected source files; its numerical results remain author-reported. The hybrid is an engineering synthesis, not a measured competitor. Source revisions and measurement conditions must accompany any independent reproduction.

- A1: Aether 5b732971 - waveform specification
- A2: Aether - receiver
- A3: Aether - committed scenario results
- A4: Aether - granted-slot design and timing bounds
- D1: Data2G 29c97646 - mode constants
- D2: Data2G - coding and HARQ
- D3: Data2G - estimator/refinement
- D4: Data2G - speed-test evidence
- M1: Mercury v2 f77adfb7 - modes and limitations
- M2: Mercury - OFDM parameters
- M3: Mercury - repair carousel
- I1: Ion 1eb7dca0 - status and license
- I2: Ion - PHY, power, pilot design and limitations
- I3: Ion - ladder, HARQ, cue, channel reports and streaming
- I4: Ion - MFSK and severe-channel evidence
- I5: Ion - FEC
- I6: Ion - estimator and error-aware demapping; refinement is in phy/rx/refine.rs
- I7: Ion - constrained goodput selector
- I9: Ion - Lifeline
- I10: Ion - outer-repair stream
- I11: Ion - IONOS results and calibration
- I12: Ion - Mercury 1.9.21 comparison
- I14: Ion - notices and credit
- T1: Cui, Tellambura and Wu - BEM channel estimation and iterative ICI equalization
- T2: ITU-R F.1487 - HF channel-model testing methodology

X1: xara snapshot `361a30cd`**.** Reviewed paths include `crates/xara-phy/src/hf/level.rs`, `rx/ofdm.rs`, `tx.rs` and `crates/xara-arq/src/hf/session.rs`. This source was a local review snapshot; no portable public source URL is established in this register. Its comparison rows are source-analysis findings, not independent performance measurements.