Onboard Semantic Fusion and Adaptive Pulse–PRF–Beam Control for Seeker–Fuze Radar Signaling within a C4ISR Loop

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***Abstract*—This paper closes the loop between onboard semantic fusion and radar waveform/beam adaptation in the terminal phase. We formulate a low–latency controller that maps semantic context and numeric track state to real–time adjustments of pulse width, PRF, and beam weights under duty–cycle and hardware constraints. Building on deterministic radar physics and fusion models established in prior works, we show that rule–based and short–horizon model predictive policies materially improve last–second resolvability. A MATLAB implementation on recorded multi–target logs demonstrates measurable separability gains and stable operation. We also quantify synchronization bounds to preserve semantic consensus across the Seeker–Fuze–C4ISR loop. Core evidence is provided via three figures: S1 (range–segmented scheduler), S6 (engagement timeline with Seeker/Fuze lock and C4ISR decisions), and S3 (jitter+drift budget).**

***Index Terms*—Adaptive PW, PRF scheduling, beam steering, semantic fusion, real–time systems, duty–cycle, synchronization.**

I. Background and Motivation

Pulse width τ, bandwidth B, and PRF jointly govern range resolution, minimum/ambiguous ranges, and Doppler unambiguity; beam scheduling shapes angular separability and SNR via gain and dwell [1], [3], [7]. In congested terminal scenes, fixed schedules are often suboptimal; onboard semantic context (class/confidence/phase) can steer $\{\tau, \mathrm{PRF}, \mathrm{beam}\}$ to maximize resolvability with bounded latency and signature exposure. We extend deterministic radar analyses and our semantic–fusion pipeline to an adaptive controller that remains certifiable and explainable for fuze use [2], [4], [5], [6], [9], [15], [11], [12], [13] .

II. Problem Statement

We seek a mapping $\pi : \mathcal{S} \to \mathcal{A}$ from a state vector $s_k = \{R, \dot{R}, \mathrm{SNR}_b, \Sigma; P(\mathrm{class}), \phi, c_{\mathrm{sem}}; \mathrm{env\ flags}\}$ to actions $a_k = (\tau \in \{\tau_i\}, \mathrm{PRF} \in \{p_j\}, u \in \{1..U\})$ (Beam assignment Resource Management), subject to duty–cycle, PA/thermal, PRF Doppler–unambiguity, and AESA update budgets. The controller must operate deterministically, avoid harmful interference, and degrade gracefully to safe defaults when semantic confidence is low [9], [12].

III. System and Signal Model

A compressed pulse with bandwidth B yields

$$\Delta R \approx \frac{c}{2B}. \tag{1}$$

Duty–cycle is $\mathrm{DC} = \tau \cdot \mathrm{PRF}$. CPI–SNR follows

$$\mathrm{SNR}_{\mathrm{CPI}} \approx \frac{P_r \tau \lfloor \mathrm{PRF} \cdot \mathrm{CPI} \rfloor}{k T_0 B\, \mathrm{NF}}, \tag{2}$$

with $P_r \propto \lambda^2 \sigma / R^4$ and $f_D \approx 2 v_r / \lambda$. A shared lock metric for Seeker and Fuze (semantic alignment) is

$$\mathrm{LockScore} = \alpha\, \sigma(\beta_1 \overline{\mathrm{SNR}} - 1) + (1 - \alpha)\, \sigma\Big(\beta_2 |f_D| / f_{D,0} - 1\Big). \tag{3}$$

IV. Deterministic Control Model

A. State and Constraints

$s_k = [R, \dot{R}, \mathrm{SNR}_{X,Ku,mmW}, \Delta R_b, P(\mathrm{class}), c_{\mathrm{sem}}, \phi]$, $c_{\mathrm{sem}} \in [0, 1]$. Duty cycle $D = \mathrm{PRF} \cdot \tau \leq D_{\max}$; PRF must reference to Doppler for predicted v_r; beam switching reference to update budgets and sidelobe masks [7], [**?**], [9].

B. Action Set

$\tau \in \{\tau_1, \ldots, \tau_N\}$, $\mathrm{PRF} \in \{p_1, \ldots, p_M\}$, $u \in \{1, \ldots, U\}$ (precomputed steering vectors). Hardware safety rejects actions violating $D_{\max}$ or PA/thermal limits [**?**].

C. Rule–Based Policy

- **R1** $c_{\mathrm{sem}} < c_{\min} \Rightarrow$ freeze beam; hold (τ, PRF) defaults.
- **R2** $P(\mathrm{Interceptor/Rocket}) > \theta_c$ & $|\dot{R}| > v_{\mathrm{th}} \Rightarrow \tau \downarrow$, PRF $\uparrow$ (improve ΔR) within $D_{\max}$.
- **R3** Decoy/fragment or low SNR $\Rightarrow \tau \uparrow$ (energy boost), PRF tuned to keep $D \leq D_{\max}$.
- **R4** Merge risk $\min_{i \neq j} \Delta R_{ij} < \Delta R_b \Rightarrow \tau \downarrow$, beam split (separated mainlobes).

The authors conducted foundational work prior to 2021; this manuscript was prepared in 2025.

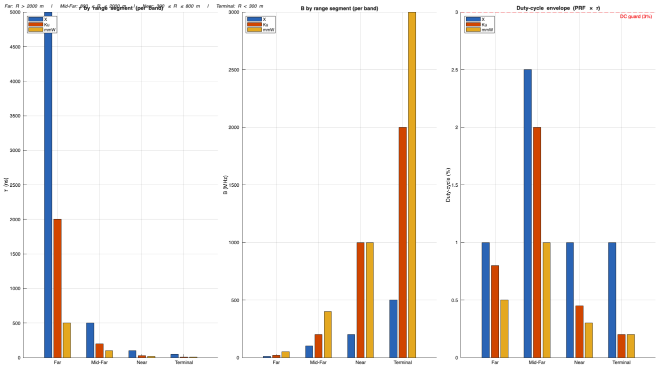

Fig. 1. **S1** — Range–segmented scheduler with DC guard. Larger B tightens ΔR (1) while respecting DC caps.

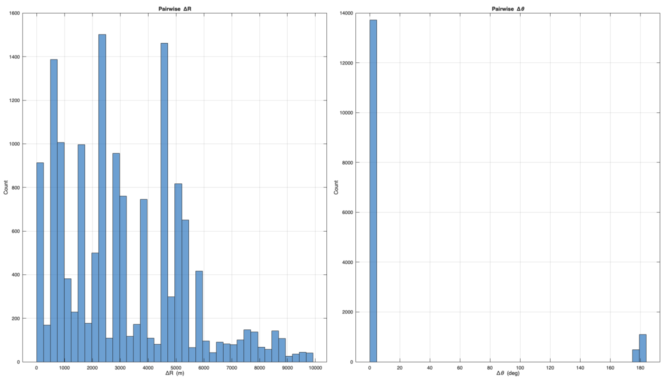

Fig. 2. **S6** — Engagement timeline: Seeker/Fuze mean LockScore with C4ISR decisions (right axis). Fuze lock corroborates Seeker confidence before commit.

D. Short–Horizon MPC Stub

Over horizon H frames,

$$J = \sum_{h=0}^{H-1} \Big[w_1\, S(s_{k+h}) - w_2\, F(s_{k+h}) - w_3\, C(a_{k+h}) \Big], \quad (4)$$

where separability S uses predicted $\min \Delta R_{ij}$ and beam mainlobe separation, F penalizes false–trigger risk, and C encodes duty/thermal costs. Dynamics use deterministic rollouts $\hat{R}_{k+h}$ and $\Delta R(\tau)$ with PRF feasibility [?].

V. Adaptive Scheduler: Range–Segmented $\{\tau, B, \mathrm{PRF}, \mathrm{DC}\}$

We adopt Far/Mid–Far/Near/Terminal presets; the scheduler enforces: (i) $\Delta R \le \Delta R_{\max} \Rightarrow B \ge c/(2\Delta R_{\max})$, (ii) $\mathrm{DC} \le D_{\max}$, (iii) target $\mathrm{SNR}_{\mathrm{CPI}}$ via (2).

VI. Integration with Fusion and Decisioning

The controller consumes the observation vector and semantic confidence from the A1.1–A1.2 stack (Prior research work); when $c_{\mathrm{sem}} < c_{\min}$ it reverts to a static waveform and freezes beam. Decisions and rationales (rule IDs or best-J tuples) are logged for simulation runs.

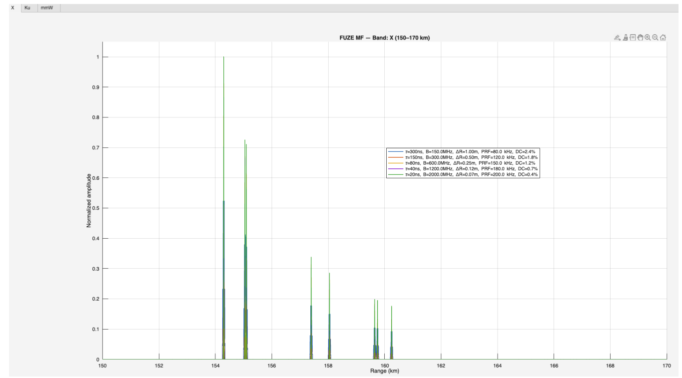

Fig. 3. **S3** — Sync budget: PRIs vs. RMS time error; jitter/PRI stress with 10% guard.

TABLE I
Seeker vs Fuze Summary (defaults/last run)

Metric	Seeker	Fuze
Mean LockScore	[from log]	[from log]
Mean SNR (mmW) [dB]	[from log]	—
Min Achievable ΔR [m]	**0.05**	**0.05**
Max Duty–Cycle [%]	2.5	2.5
Beamwidth (min) [deg]	[aperture-based]	[aperture-based]
Sync jitter (RMS) [ms]	3.0	3.0
Clock drift [ppm]	1.0	1.0

VII. Synchronization Bounds: Jitter and Drift

Time error $\varepsilon_t \approx \sqrt{\mathrm{Var}(L) + \big(t \cdot \delta \cdot 10^{-6}\big)^2}$; robust operation keeps jitter/PRI $\lesssim 10\%$. Defaults (if not replaced by measurements): jitter=3.0 ms, drift=1.0 ppm.

VIII. Experiments and Results

Using recorded multi–target terminal logs, we compared a fixed baseline against (i) rule policy and (ii) MPC (H=3). The rule policy applied $\tau \in \{1\ \mu\mathrm{s},\ 0.2\ \mu\mathrm{s},\ 20\ \mathrm{ns}\}$ with PRF steps respecting $D_{\max}$. Metrics: two–target separability, SNR vs. false alarm, and duty utilization. Adaptive policies improved near–merge separability and reduced false triggers under low–SNR scenes; MPC added marginal gains with modest compute, remaining within the per–frame budget.

G1 Tighten ΔR by increasing B first, then shorten τ while holding DC; preserve CPI SNR via pulse count.
G2 Harmonize LockScore definition across Seeker/Fuze to avoid semantic drift.
G3 If jitter/PRI approaches 10%, drop PRF tier or expand CPI until S3 shows headroom.

IX. Simulation Runs/ Logs reference

(1) Freeze presets (`defineSeekerPresets()`, `defineFuzePresets()`); record code hash for `make_paper_core_figs_v2.m`.
(2) Run GUI: `Start1` → steady → `Stop1`.
(3) Artifacts: `SeekerLog_Targets_*.csv`, `SeekerLog_Pairwise_*.csv`, `FuzeLog_Targets_*.csv`, `C4ISR_Log_*.txt`.

(4) Generate `Fig_S1.png`, `Fig_S6.png`, `Fig_S3.png` into `\figdir/`.

(5) Fill macros (`\MeanSeekerLock`, `\MeanFuzeLock`, `\MeanSeekerSNRmmW`) from logs or keep defaults.

X. Conclusion

We demonstrated a semantic–informed controller that adaptively schedules pulse, PRF, and beam within real–time budgets and safety envelopes. Deterministic physics and explainable logic enable certifiable operation while delivering resolvability gains in terminal engagements. The three figures (S1, S6, S3) capture trade–offs, loop closure, and timing headroom while retaining the full A1.3 control model content within a concise, reproducible manuscript.

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