Volume 1

CHAPTER 3

CBTC System Architecture Overview

Communications-Based Train Control
A Comprehensive Guide for US Transit Professionals
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Chapter Overview

- Position CBTC within the larger transit ecosystem — system context and external interfaces (IEC 62290)
- Decompose the ATC triad: ATP (safety) + ATO (performance) + ATS (operations)
- Map functional architecture onto three physical hardware tiers: onboard, wayside, and central
- Trace real-time data flow patterns — the 'heartbeat' cycle that drives moment-to-moment train control
- Evaluate the critical architectural decision: overlay vs. standalone CBTC deployment

3.1

System Context and Interfaces

ATP / ATO / ATS Triad Architecture

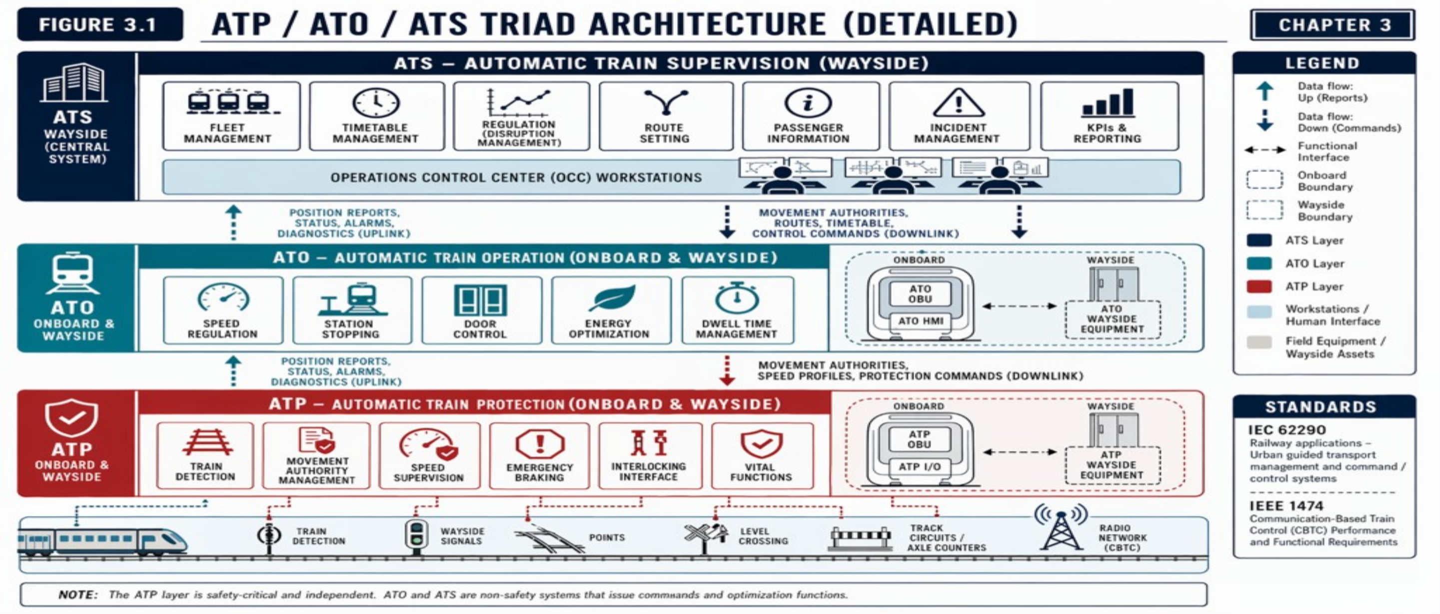

Figure 3.1 — The three functional layers of CBTC: ATP (safety), ATO (performance), ATS (supervision).

CBTC System Boundary (IEC 62290)

- CBTC comprises ATP + ATO + ATS — everything else is external with defined interfaces
- Electronic Interlocking (EI): manages switches and signals; CBTC sends route commands, receives confirmation
- SCADA: supervises traction power, ventilation, lighting — interfaces via OPC-UA or proprietary APIs
- Platform Screen Doors: independent safety system — CBTC issues stop signal, PSD verifies independently
- PIS, AFC, BAS, Depot Management: non-safety interfaces for passenger info, fare, and facilities

Why Interface Management Is Critical

- Interface design and testing consume ~40% of system integration cost (WMATA experience)
- Common failure: undefined interface specs — CBTC vendor and PSD vendor interpret requirements differently
- Latency mismatch: CBTC operates at 100ms cycles; legacy SCADA may update every 2–5 seconds
- Protocol incompatibility: new CBTC uses OPC-UA; legacy EI speaks Modbus — requires gateway devices
- Best practice: early system context analysis, explicit ICDs, phased integration testing, independent safety audit

3.2

Functional Architecture — ATC = ATP + ATO + ATS

End-to-End CBTC Architecture

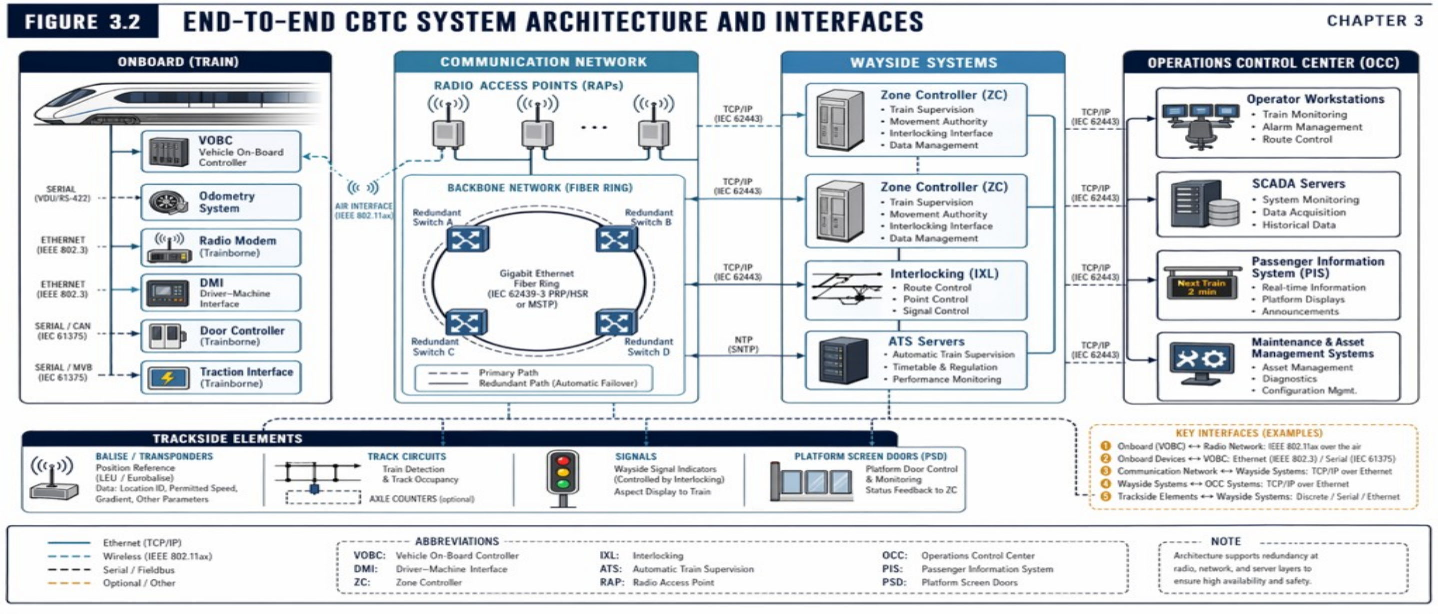

Figure 3.2 — End-to-end CBTC system architecture and interfaces.

ATP: The Safety-Critical Foundation

- Mandatory in ALL CBTC systems (GoA 0–4) — the non-negotiable safety floor
- Five essential functions: speed supervision, MA management, safe separation, rollback protection, door logic
- Must achieve SIL 4: redundant channels, diverse programming, formal verification, safe-state bias
- The ATP envelope: speed-vs-distance boundary defining maximum safe speed at each point ahead
- If ATP conflicts with ATO or driver commands, ATP wins — the train brakes immediately

ATO and ATS: Performance & Operations

- ATO — Performance Optimizer:
- Speed regulation to meet timetable targets
- Precision stopping: ±30 cm accuracy at platforms
- Energy optimization: 10–20% savings via coasting profiles
- Mandatory at GoA 3/4; optional at GoA 1/2

- ATS — Operational Intelligence:
- Timetable management and schedule regulation
- Automatic route setting at junctions
- Conflict detection and resolution
- SIL 0 — advisory only; dispatcher can override

ATP, ATO, ATS at a Glance

Attribute	ATP	ATO	ATS
Function	Safe speed & separation	Optimize speed & stops	Manage timetable & routes
SIL	SIL 4 (mandatory)	SIL 0–2	SIL 0
Authority	Final — overrides all	Over ATS; under ATP	Advisory
Failure Impact	Safety hazard	Performance degradation	Scheduling disruption
Redundancy	Yes (functional & diverse)	Partial	No

3.3

Physical Architecture: Onboard, Wayside, Central

Three-Tier Physical Architecture

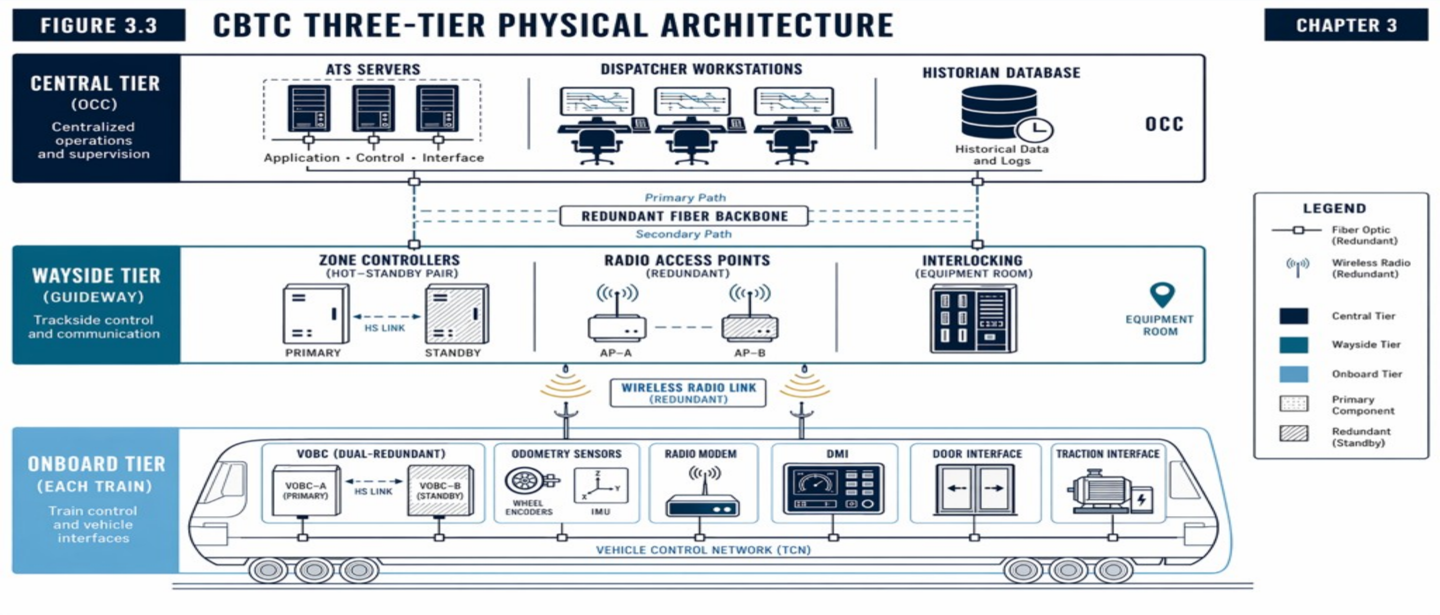

Figure 3.3 — CBTC three-tier physical architecture: onboard, wayside, and central systems.

Onboard and Wayside Tiers

- Onboard Tier (per train):
- VOBC: dual/triple redundant processors (SIL 4)
- Radio unit: 500 kbps–2 Mbps dedicated link
- Sensors: tachometers, Doppler radar, balise antenna
- DMI: 7–10" touchscreen for driver awareness
- Cost impact: $500K–$1.5M per vehicle

- Wayside Tier (per zone):
- Zone Controller: 2–5 km zones, hot-standby pairs
- Wayside Access Points: radio coverage along track
- Transponders/balises: absolute position references
- Equipment rooms: 20m², redundant power, HVAC
- Cost: $400K–$700K per zone controller pair

Central Tier: ATS and Network Backbone

- ATS server: real-time fleet management, timetable optimization, conflict resolution
- Dispatcher workstations: graphical overview of all train positions and system status
- Data recording: event logs, performance analytics, incident investigation support
- Redundant network backbone: fiber-optic ring connecting all zones and central systems
- Typical 20 km line: 5–8 zones, 40–60 trains, 2 redundant ATS servers

3.4

Data Flow and Communication Patterns

The CBTC Heartbeat Cycle

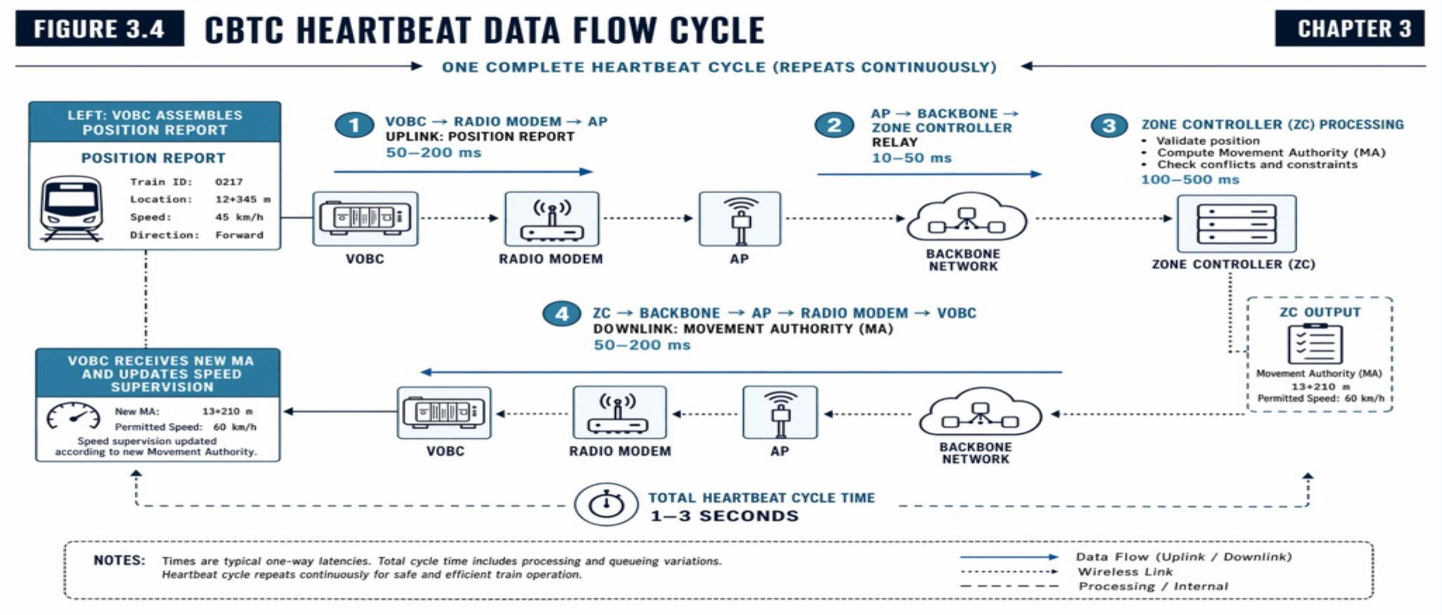

Figure 3.4 — Real-time data exchange: position reports up, Movement Authorities down, every 0.5–3 seconds.

Communication Patterns

- Train → Wayside: position reports every 500ms–1s (location, speed, status, door state)
- Wayside → Train: Movement Authorities every 1–3s (safe distance, speed profile, route info)
- Wayside ↔ Central: ATS commands (dwell targets, route setting) and real-time train data
- Communication loss handling: train enters degraded mode; reduced speed; re-initialization required
- Latency budget: end-to-end <500ms for safety-critical commands; <2s for supervisory data

3.5

Overlay vs. Standalone CBTC

Overlay vs. Standalone CBTC

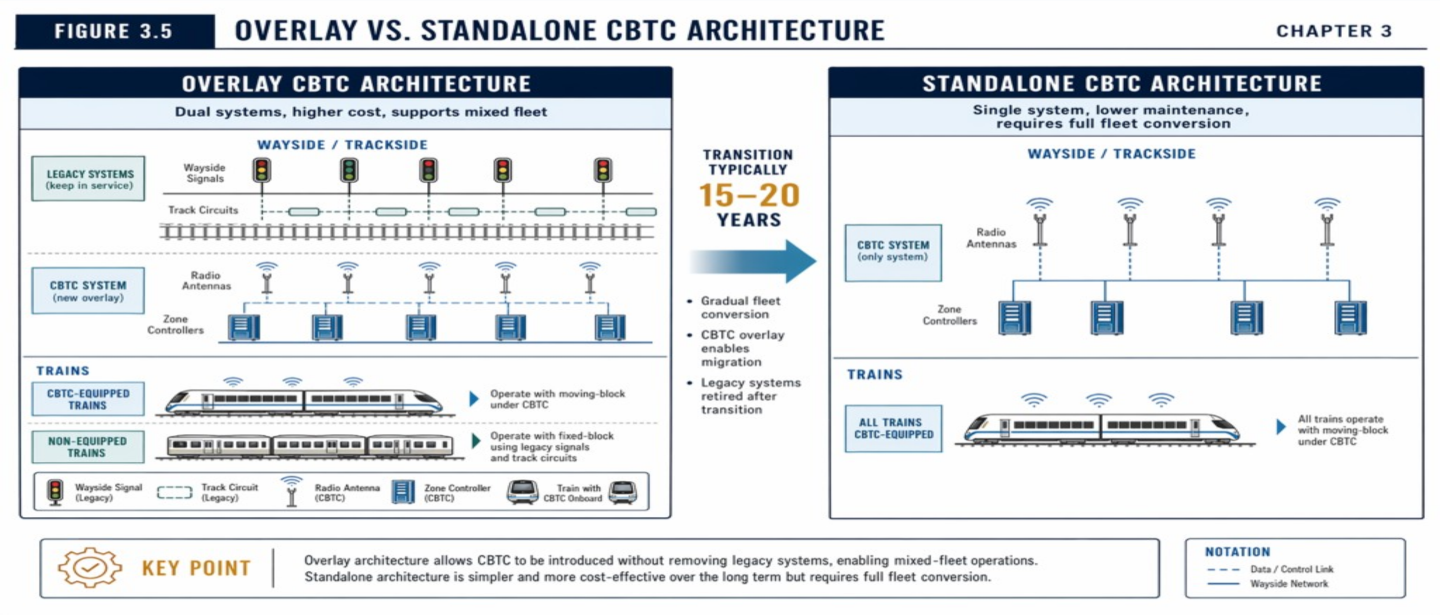

Figure 3.5 — Overlay retains legacy signals; standalone eliminates them entirely.

Overlay vs. Standalone Trade-offs

- Overlay CBTC (most US retrofits):
- Retains legacy signals and track circuits for fallback
- Allows mixed CBTC / non-CBTC fleet operation
- Higher ongoing maintenance (dual systems)
- NYC L Line, BART, WMATA — all overlay

- Standalone CBTC (new-build systems):
- Eliminates wayside signals entirely
- Lower lifecycle cost (single system)
- Requires full fleet CBTC-equipped
- Paris Line 14, Copenhagen, Dubai Metro

Key Takeaways

1. CBTC architecture separates concerns: ATP (safety floor, SIL 4) > ATO (performance optimization) > ATS (line-level operations, SIL 0)

1. The system-of-systems perspective is critical — interface management consumes ~40% of integration cost and is the leading cause of project delays

1. Three physical tiers (onboard, wayside, central) map cleanly to functional layers; each tier has distinct hardware, cost, and environmental requirements

1. The heartbeat cycle — position reports up, Movement Authorities down — drives real-time train control with sub-second latency requirements

1. Overlay vs. standalone is the defining architectural decision for US retrofits: overlay enables phased deployment but doubles maintenance burden

End of Chapter 3

Next: **Chapter 4: Onboard Equipment**

Questions & Discussion

