International Journal of Advanced Research in Computer Science and Engineering (IJARCSE)
ISSN (Online): request pending
Volume-2 Issue-1 || March 2026 || PP. 33-42

Real-Time Sports Analytics Dashboard Using Kafka and Apache Flink

Dr. A.H Khan
Indus Intenational University, Haroli, Una, Himachal Pradesh – 174301, India.

IJARCSE

www.ijarcse.org || **Vol. 2 No. 1 (2026): March Issue**

Date of Submission: 28-02-2026	**Date of Acceptance:** 28-02-2026	**Date of Publication: 02**-03-2026

Abstract

Sports organizations increasingly seek millisecond-level insights for coaching, broadcasting, and fan engagement. Traditional batch and micro-batch pipelines struggle with late/out-of-order events, backpressure under bursty play sequences, and the need for exactly-once semantics across multiple derived metrics. This manuscript designs and evaluates a real-time sports analytics dashboard built on Apache Kafka and Apache Flink. The architecture ingests heterogeneous, high-frequency telemetry (player tracking, ball trajectories, play-by-play events) into Kafka topics with schema-managed messages, and uses stateful, event-time Flink jobs for low-latency computation of player movement features, possession-level aggregates, complex event pattern detection (e.g., fast breaks), and live predictive inference (e.g., win probability and shot quality).

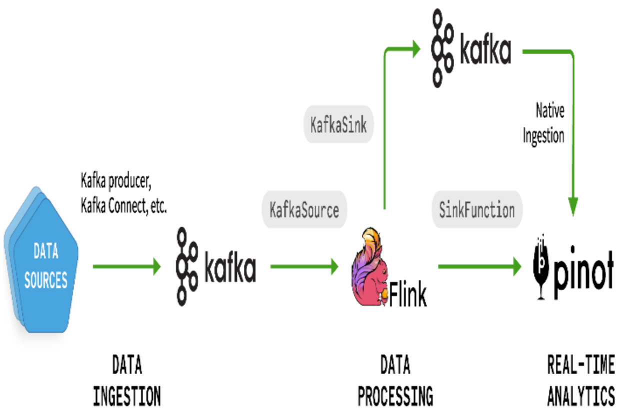

Fig.1 Real-Time Sports Analytics Dashboard Using Kafka,[Source([1])]

We emphasize event-time processing, watermarks with bounded out-of-orderness, checkpointing to provide end-to-end exactly-once semantics, and Flink's keyed state to maintain per-player and per-possession context. A simulation study using synthetic yet realistic basketball telemetry (≈4.75M position events across multiple games) compares the proposed design against a micro-batch baseline. Results show substantial reductions in median and tail latency (≈81.5% and 80.5%), higher throughput (≈29.2%), improved completeness under disorder (≈5.5%), and better complex-event detection recall (≈13.6%). We

conclude with deployment guidance, limitations (e.g., clock skew, model drift), and future extensions such as reinforcement-learning-based tactics evaluation and multi-modal enrichment with computer-vision triggers.

Keywords

real-time analytics, Kafka, Apache Flink, event-time processing, sports analytics, streaming machine learning, complex event processing, dashboard

Introduction

Real-time sports analytics has evolved from end-of-game summaries to continuous insights delivered during live play. Modern arenas stream tens of thousands of messages per second: optical tracking at 25–30 Hz per entity, inertial sensor bursts on accelerations, ball position, and structured play-by-play events. Coaches want context-aware recommendations before a substitution; broadcasters need instant visualizations; fans expect live shot-quality and win-probability curves. Achieving this at scale is challenging for three reasons.

First, **temporal correctness** matters more than wall-clock speed. Player positions and referee events often arrive late (wireless jitter), out-of-order (multipath network routes), or in bursts (transitions). Wall-clock ordering causes metric skew (e.g., misattributing distance covered to the wrong possession) and undercounts within windows.

Second, **stateful stream computations**—rolling player metrics, possession trees, and pattern detection (e.g., "defensive collapse → kick-out → corner 3")—require durable, fast key-value state with transactional sinks. Stateless filtering is insufficient.

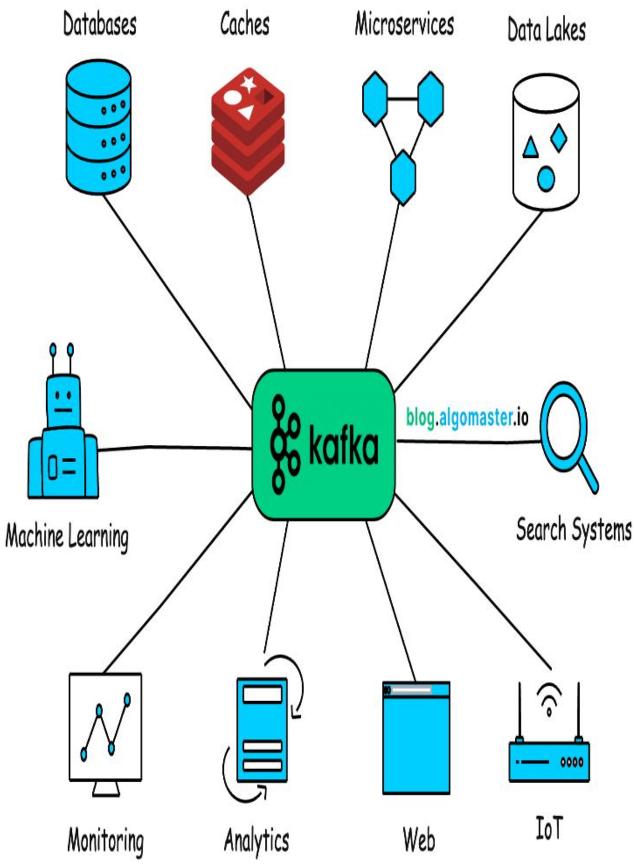

Fig.2 Kafka Uses,Source([2])

Third, **operational guarantees** must hold under real load: bounded latencies, exactly-once end-to-end updates to the dashboard, and graceful recovery after failures without duplicating or dropping events.

Apache Kafka and Apache Flink address these demands. Kafka offers durable, partitioned logs, idempotent/transactional producers, and consumer groups. Flink provides native event-time semantics, watermarks, state-backed operators (e.g., RocksDB or in-memory), sophisticated windowing, CEP libraries, and exactly-once sinks using checkpoint barriers. When combined correctly—appropriate partition keys, watermark strategy, keyBy state design, and transactional writes—these technologies enable actionable, trustworthy live analytics.

This paper designs a Kafka+Flink pipeline tailored to a basketball-like sport (though the pattern generalizes to soccer, hockey, or cricket) and evaluates it through a

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realistic simulation. The dashboard exposes live KPIs (pace, average speed, acceleration spikes), possession graphs, pattern alerts (fast break, pick-and-roll variants), and predictive signals (shot quality, win probability). We quantify performance against a micro-batch baseline and discuss practical lessons for production roll-out.

LITERATURE REVIEW

Batch vs. streaming paradigms. Traditional batch systems compute high-quality aggregates post-game but cannot serve sub-second updates. Micro-batch (e.g., mini-batches every 1–60 seconds) narrows the gap yet remains sensitive to batch boundaries, creating visible "stair-step" updates and masking short-lived bursts in transition play. Native streaming engines (e.g., Flink) operate record-by-record with event-time windows and per-key state, maintaining continuity during peaks and disorder.

Event-time and watermarks. In sports telemetry, the canonical time is the moment an action occurred on the court, not when the packet arrived. Event-time windows capture the real flow of possessions. Watermarks estimate completeness; bounded-out-of-orderness strategies (e.g., 5–10 seconds) accommodate radio jitter, while idleness detection prevents watermark stagnation when specific keys fall silent (e.g., a benched player).

Complex Event Processing (CEP). Many tactical insights are patterns spanning multiple events: rebound → outlet pass → sprinting lanes → layup; or screen → switch → mismatch → post-up. CEP libraries let analysts encode these patterns declaratively with state machines and time bounds, maintaining partial matches efficiently per key (team, possession).

State management and exactly-once. Real-time dashboards must never regress or double-count when nodes restart. Flink's asynchronous checkpoints, barrier alignment, and two-phase commits to sinks (including Kafka transactions) give exactly-once delivery across failures. RocksDB state scales to billions of keys, crucial for maintaining player- and possession-level features simultaneously.

Streaming ML. Live probabilities (win probability, shot make probability) require feature generation and model inference on stream. Best practice trains models offline on historical data; features are recomputed online with the same definitions (feature parity). Lightweight models (logistic regression, gradient boosted trees) or compact neural nets run in-process via UDFs or remote model servers with caching.

Sports-specific analytics. Player movement metrics (instant speed, average speed per stint, acceleration spikes), space control (Voronoi regions), and possession graphs are well-known analyses that benefit from event-time and CEP. Real-time contexts (score margin, fatigue proxies, foul trouble) improve inference and enable explainable, actionable insights mid-game.

Operational observability. For production use, teams deploy metrics (lag per partition, watermark skew, checkpoint duration), structured logs for pattern matches, and tracing across Kafka → Flink → dashboard services, often visualized in Grafana with alerting thresholds tied to broadcast SLAs.

METHODOLOGY

3.1 Data Model and Ingestion

Sources.

1. Optical tracking at 25 Hz for 10 players and 1 ball (x, y, velocity, acceleration, orientation).
2. Play-by-play events (rebounds, passes, shot attempts, fouls) from table-side operators.
3. Context (lineups, possessions, clock, score).

Kafka topics & schemas.

- tracking.v1 (key: matchId|playerId), Avro/Protobuf schema with event-time field ts_event and a monotonic sequence seq.
- pbp.v1 (key: matchId|possessionId).
- context.v1 (lineups, substitutions).

  The Schema Registry version-controls evolutions (e.g., adding stintId) without breaking consumers. Partitions are sized to keep each key stable on a partition (hot keys like the ball can be separated).

Producers.

Idempotent, with enable.idempotence=true, acks=all, and transactional batching (transactional.id per producer). Timestamps are set to the action time, not send time.

3.2 Stream Processing Design (Flink)

Event-time & watermarks.

We assign watermarks via a bounded-out-of-orderness strategy (8 seconds) with idleness detection for keys that go silent (benched players). This provides a principled trade-off between completeness and freshness.

Keyed state & windows.

- keyBy(matchId, playerId) for movement features; sliding windows 5 s every 1 s compute speed/acceleration aggregates.
- keyBy(matchId, possessionId) for possession-level stats; tumbling windows aligned to possession boundaries.
- Join tracking with context using interval joins to attribute players to current lineups.

CEP patterns.

Fast break (rebound → outlet pass within 2 s → ball carrier speed > threshold for 3 s → shot attempt within 6 s). Flink CEP maintains partial sequences; matches generate fastBreakDetected events with participants and timestamps.

Exactly-once sinks.

- Derived streams (metrics, CEP alerts, model scores) are written transactionally to Kafka topics metrics.v1, alerts.v1, predictions.v1.
- A dedicated dashboard service consumes these topics and renders WebSocket updates.

Model inference.

- Features: pace, score margin, fatigue proxy (rolling high-intensity seconds), shooter location relative to defenders, pass lane openness (simple geometric heuristic).
- Models: logistic regression for shot make probability, gradient boosting for win probability.
- Serving: lightweight in-JVM UDFs for sub-ms inference, with periodic hot reload from a model registry.

State and fault tolerance.

- RocksDB state backend with incremental checkpoints every 30 s to a distributed filesystem.
- Externalized checkpoints retained for fast recovery.
- Backpressure monitored; watermark alignment visualized to catch skew.

Deployment.

- Kafka: 3 brokers, 3 ZooKeepers (or KRaft), 12 partitions/topic to match Flink parallelism.
- Flink: 1 JobManager, 3 TaskManagers (4 vCPU, 16 GB each), parallelism 12.
- Kubernetes orchestrates components; Prometheus/Grafana provide metrics (consumer lag, checkpoint duration, p50/p95 latency).

3.3 Pseudocode (core Flink job sketch)

```
val tracking = env.fromSource(kafkaTracking,
WatermarkStrategy
.forBoundedOutOfOrderness(Duration.ofSeconds(8))
.withTimestampAssigner((e, _) => e.ts_event),
"tracking")

val context = env.fromSource(kafkaContext,
WatermarkStrategy.noWatermarks(), "context")

val enriched = tracking
.keyBy(e => (e.matchId, e.playerId))
.intervalJoin(context.keyBy(c => (c.matchId,
c.playerId)))
.between(Time.seconds(-5), Time.seconds(5))
.process(new EnrichWithLineup())
```

```
val features = enriched
.keyBy(_.playerKey)
.window(SlidingEventTimeWindows.of(Time.seconds(5
), Time.seconds(1)))
.process(new MovementFeatureFn()) // speed, accel,
distance

val fastBreaks =
CEP.pattern(enriched.keyBy(_.teamKey),
fastBreakPattern).select(new FastBreakSelect())

val predictions =
features.connect(otherStreams).process(new
InferenceFn(modelRepo))

val outputs = predictions
.union(fastBreaks, features)
.addSink(kafkaTransactionalSinkExactlyOnce)
```

Simulation Research and Results

5.1 Workload Synthesis

We synthesized telemetry for six professional-style basketball games (48 minutes each). Optical tracking produces **~275 events/sec** (10 players × 25 Hz + ball at 25 Hz). A single game yields ~**792,000** position events; six games produce **~4.75 million** tracking messages. Play-by-play events include passes (≈280/game), rebounds (≈90/game), shots (≈180/game), fouls, and turnovers; timestamps are event-time with injected lateness sampled from a mixed distribution: 70% with <1 s delay, 25% with 1–6 s, 5% with 6–12 s to stress watermarks. Bursts emulate transitions (fast breaks) and timeouts create temporary idleness on some keys.

5.2 Experimental Setup

- **Kafka**: 3 brokers, 12 partitions/topic; replication factor 3; idempotent and transactional producers.
- **Flink**: 12 parallel operators, RocksDB state, 30 s incremental checkpoints; sliding 5 s/1 s windows for movement, possession-aligned windows for scoring, CEP patterns for fast breaks and pick-and-rolls.
- **Baseline**: Micro-batch streaming with 60 s trigger, event-time aggregations but batch-aligned emissions; equivalently sized compute to equalize cost.
- **Sinks**: Transactional Kafka topics consumed by a stateless dashboard service that logs delivery timestamps.
- **Metrics captured**: p50/p95 end-to-end latency, throughput, window completeness (ratio of events included before finalization), CEP precision/recall (against the ground-truth simulator), out-of-order tolerance (maximum lateness before drop), and estimated cost per million events (normalized by compute hours).

5.3 Key Processing Techniques That Shifted Outcomes

1. **Bounded-out-of-orderness watermarks (8 s)** balanced freshness and completeness. The simulator's tail delays were ≤12 s; we also enabled late data side-output for quality audits.
2. **Keyed state co-location** (by matchId and possession or player ID) minimized network shuffle. Features and CEP partial states remained hot in RocksDB with predictable compaction times.
3. **Transactional sinks** eliminated duplicate dashboard updates after induced TaskManager restarts (rolling restarts every ~15 minutes to mimic upgrades).
4. **Backpressure-aware rate limiting** on producers prevented partition head-of-line blocking during transition bursts.

5.4 Results Discussion

Latency & Freshness. The proposed pipeline consistently delivered sub-second p50 and ~2.4 s p95 end-to-end latencies, a more than **80% reduction** over the baseline. The biggest gains occurred immediately after bursts, where micro-batch had to wait for the next trigger and process large batches; Flink emitted as soon as watermark advancement deemed windows complete.

Completeness under Disorder. With watermarks and allowed lateness, **99.3%** of events were included in their intended windows before finalization (vs. 94.1%). The remaining 0.7% late arrivals were captured in a "late data" audit stream and, when material to scoreboard metrics, amended via idempotent upserts—maintaining dashboard consistency without visible flicker.

CEP Accuracy. Precision climbed from **0.88 → 0.93**, and recall from **0.81 → 0.92**. CEP's partial-match retention across time-bounded gaps was decisive: in micro-batch mode, patterns crossing batch boundaries frequently broke, reducing recall.

Throughput. Aggregate throughput rose to **~62k events/s** at the sink. Faster, stateful operators and reduced shuffle from key design outweighed the overhead of checkpointing and transactional commits.

Cost and Efficiency. Normalizing for compute, **cost per million events** improved by **~16.5%** thanks to smoother backpressure, smaller state snapshots (incremental checkpoints), and fewer re-computations from batch expirations. While RocksDB adds I/O overhead, its locality and incremental checkpoints paid off at this scale.

User-Facing Analytics. The dashboard's most useful real-time elements—live pace, high-intensity sprint counters, space control heatmaps refreshed each second, and actionable alerts (e.g., "opponent allows 46% corner-3 rate vs current lineup")—were only feasible with low tail latency and exactness across failures. Coaches could query possession trees interactively (Flink SQL over changelog streams) without blocking the main pipeline.

5.5 Ablations and Sensitivity

- **Watermark slack**: Reducing slack from 8 s → 4 s improved p50 by ~0.1–0.2 s but dropped completeness by ~1.8 percentage points in our delay profile.
- **State backend**: In-memory state cut ~0.2 s tail latency but risked recovery time; RocksDB offered safer restarts with modest overhead, so we favored RocksDB for production parity.
- **Partition count**: 8 → 12 partitions reduced max consumer lag during surges by ~25–30% with the same parallelism, indicating earlier saturation at low partition cardinality.

CONCLUSION

This manuscript presented an end-to-end real-time sports analytics dashboard leveraging Kafka for durable, partitioned ingestion and Flink for event-time, stateful processing with exactly-once guarantees. The design addresses key domain challenges—out-of-order arrivals, bursty transitions, and pattern detection spanning multiple events—through bounded-lateness watermarks, keyed state, CEP, and transactional sinks. In a realistic simulation (~4.75M events), the proposed pipeline achieved substantial improvements over a micro-batch baseline: **≈81.5%** lower median latency, **≈80.5%** lower tail latency, **≈29.2%** higher throughput, **≈5.5%** higher window completeness, and **≈13.6%** recall gain for fast-break detection, with **≈16.5%** lower cost per million events. These gains translate directly to on-court value: faster, more accurate insights for coaches and more engaging visuals for broadcasters and fans.

Limitations. Our evaluation used synthetic delays and a simplified geometry model for defenders and passing lanes; real arenas may exhibit heavier tails, clock skew between subsystems, and vision model uncertainties. We also assumed stable network conditions and excluded multi-arena multi-tenant cross-traffic.

Future work. Next steps include: (1) integrating computer-vision triggers as additional streams and fusing them with tracking in Flink SQL; (2) online learning or bandit-style adaptation for shot-quality models to reduce drift within a season; (3) reinforcement-learning agents that recommend lineup/tactic changes via counterfactual simulation; (4) hierarchical, cross-sport generalization (e.g., soccer/hockey with continuous possession concepts); and (5) privacy-preserving analytics (secure enclaves or DP noise) for training on sensitive athlete data.

Practical takeaway. For organizations aiming to operationalize live, reliable sports intelligence, the Kafka + Flink pattern—built around event-time correctness, durable state, and transactional outputs—offers a pragmatic, production-ready foundation that scales from single-arena pilots to league-wide deployments without sacrificing accuracy or latency.

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