INTERNATIONAL JOURNAL OF ACTA INFORMATICA
VOLUME (2026)

INTEGRATING MOBILE COMPUTING AND CLOUD-BASED ENTERPRISE INFORMATION SYSTEMS

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ABSTRACT

Enterprise mobile applications are routinely used in settings, warehouses, client sites, vehicles in transit, where network connectivity is intermittent rather than continuous, yet the cloud-based enterprise information systems those applications must integrate with are typically designed around an assumption of reliable, low-latency connectivity. This paper proposes TIDE, a Tolerant, Incremental, Delta-based, Eventually-consistent framework for integrating mobile computing with cloud-based enterprise information systems, synthesizing the classical disconnected-operation and weakly connected replication literature with contemporary conflict-free replication and mobile-cloud offloading research and cloud-native architectural principles. TIDE treats a mobile client's connectivity state- synced, queuing offline, reconnecting, and merging, as a first-class part of the integration architecture rather than an edge case the backend is unaware of, recording every local write as a delta against a last-known-synced baseline and reconciling queued deltas through a conflict-resolution policy chosen per data type rather than applied uniformly. The architecture is through a connectivity-state diagram showing a disguised enterprise field-service scenario, a comparative table contrasting TIDE-guided integration against an always-online design and a naive full-resync design, and an case scenario tracing a field technician's offline work session through reconnection and merge. All quantitative figures are explicitly labeled as estimates constructed to demonstrate the framework rather than measurements from a production deployment. The paper concludes with a discussion of the limits of delta-based reconciliation and directions for empirical validation.

KEYWORDS: Mobile Computing; Cloud Integration; Offline-First Design; Data Synchronization; Conflict Resolution; Enterprise Information Systems; Disconnected Operation

INTRODUCTION

Mobile computing's integration with enterprise information systems has always had to contend with a problem desktop-oriented enterprise architecture rarely faces directly: the client's connection to the backend is not a background assumption but a condition that changes, repeatedly and often unpredictably, during the course of ordinary use, [1] description of disconnected operation in the Coda File System established, three decades before smartphones made mobile enterprise applications routine, the foundational architectural response to this condition: a client that caches enough state to keep working locally through a disconnection, logs its local changes, and reconciles them against the server once connectivity returns, rather than simply blocking or failing when the network is unavailable. [2] Bayou system extended

this reasoning to a setting with multiple, independently disconnected replicas, introducing the idea that conflicting updates made during disconnection are not necessarily errors to be prevented but an expected outcome to be detected and resolved according to an application-specific policy.

Contemporary mobile-cloud integration research has largely approached the same underlying problem from a different angle, asking how a resource-constrained mobile device can offload computation to nearby or cloud-hosted infrastructure [3] and how replicated data structures can be designed so that concurrent, disconnected updates merge automatically without requiring a central arbiter to adjudicate every conflict[4]. This paper argues that enterprise mobile-cloud integration architecture benefits from treating these two research threads, disconnected-operation-and-reconciliation and conflict-free replication, as complementary layers of a single integration framework rather than separate concerns addressed by separate tooling: the reconciliation logic Coda and Bayou pioneered determines what happens when a conflict is detected, while conflict-free replicated data types determine, for the data types where they apply, how to avoid needing that detection step at all.

This paper makes three contributions. First, it proposes TIDE, a framework that unifies delta-based offline operation with per-data-type conflict-resolution policy selection, explicitly bridging the classical disconnected-operation literature with contemporary conflict-free replication research. Second, it TIDE's core mechanism, a connectivity-state machine governing when deltas are queued, transmitted, and merged, through a disguised enterprise field-service scenario. Third, it offers a comparative analysis of TIDE-guided integration against an always-online design and a naive full-resync design, on dimensions tied to data loss risk and synchronization cost. Throughout, quantitative figures are explicitly and repeatedly labeled as estimates constructed to demonstrate the framework's reasoning, not as measurements drawn from a production system.

LITERATURE REVIEW

DISCONNECTED OPERATION AS A FOUNDATIONAL PATTERN

[1] treated disconnection not as a failure mode to be minimized but as a normal operating condition the file system's architecture should accommodate directly, caching working-set data optimistically before disconnection and logging local modifications for later replay. This reframing, from disconnection as exception to disconnection as an expected state with its own defined behavior, is the conceptual foundation this paper's TIDE framework builds on for enterprise mobile applications specifically, where field technicians, delivery drivers, and site inspectors routinely work for extended periods outside reliable network coverage.

WEAKLY CONNECTED REPLICATION AND CONFLICT DETECTION

[2] Bayou system extended disconnected operation to a setting with many independently updatable replicas rather than a single client reconciling against one server, introducing dependency checks and merge procedures that could be customized per application rather than enforced uniformly by the storage layer. This application-specific-policy approach is directly relevant to enterprise mobile integration, where different data types reasonably warrant different conflict-resolution policies: a numeric inventory count might reasonably merge via

summation of concurrent deltas, while a customer's contact information more plausibly warrants a last-writer-wins policy or explicit manual review.

CONFLICT-FREE REPLICATION

[4] formalized a class of data structures, conflict-free replicated data types, designed so that concurrent updates made on different replicas can always be merged automatically into a consistent result without requiring the kind of conflict detection and manual resolution Bayou's architecture assumes. For the subset of enterprise data types that map cleanly onto a conflict-free replicated data type, a counter, a set, a last-writer-wins register, this removes the need for explicit reconciliation logic entirely; for the data types that do not map cleanly onto any standard conflict-free replicated data type, typically because the application's correctness requirements depend on relationships between fields rather than a single field's value, Bayou-style explicit reconciliation remains necessary.

MOBILE-CLOUD OFFLOADING AND EDGE INFRASTRUCTURE

[3] cloudlet architecture addresses a related but distinct problem from the data-synchronization focus of the Disconnected Operation as a Foundational Pattern, Weakly Connected Replication and Conflict Detection, and Conflict-Free Replication subsections above: how a resource-constrained mobile device can offload computationally expensive work to nearby infrastructure rather than performing it locally or sending it all the way to a distant cloud data center. While this paper's TIDE framework focuses primarily on data synchronization rather than computation offloading, the cloudlet literature's core insight, that proximity to the mobile client materially affects what integration architecture is practical, informs TIDE's treatment of synchronization endpoints as potentially distributed across edge and cloud tiers rather than assumed to be a single, centrally located backend.

CLOUD-NATIVE BACKEND ARCHITECTURE

The elastic, pay-for-use provisioning model that characterizes the cloud-based backends enterprise mobile applications typically integrate with, and [7] situate contemporary mobile-cloud integration within the broader cloud-native computing literature, in which backend services are themselves independently scalable and independently deployable. This paper treats the specific internal architecture of the cloud-native backend as outside TIDE's scope, following the same boundary earlier papers in this line of work have drawn between an integration framework's client-facing synchronization logic and the backend's own internal service architecture, while noting that [8] distributed-systems consistency result and [9] argument for idempotent, individually retriable operations both inform why TIDE's delta-based synchronization is designed around idempotent delta application: a delta that is applied twice because a mobile client's reconnection was itself interrupted partway through synchronization must not corrupt the backend's state.

BANDWIDTH-AWARE PRIORITIZATION DURING RECONNECTION

A consideration the disconnected-operation and conflict-free replication literature reviewed above addresses only implicitly is the order in which queued deltas should be transmitted once connectivity returns, a question that matters specifically for enterprise mobile applications

because the moment connectivity returns, bandwidth is often constrained, a brief cellular signal in an otherwise disconnected area, a slow public Wi-Fi network, rather than immediately restored to full capacity. [1] Coda architecture addresses a related problem, prioritizing which files to cache before a disconnection based on predicted future access, but says comparatively little about prioritizing the reverse direction, which queued local changes to transmit first once connectivity partially returns. This paper's TIDE framework treats this as a distinct, practically important design decision: deltas affecting data other users or systems are actively waiting on, such as the parts-used inventory count in the scenario below, are transmitted ahead of deltas with no immediate downstream dependency, such as a draft note not yet ready for review, so that a brief, partial reconnection window is used for the synchronization work with the highest value rather than processed in simple chronological order.

METHODOLOGY

RESEARCH APPROACH

This paper follows a design-science approach: it synthesizes the classical disconnected-operation and weakly connected replication literature with contemporary conflict-free replication and cloud-native architecture research into a single named framework, TIDE, and that framework's reasoning using a disguised, enterprise field-service scenario rather than a production deployment. No claim is made that the quantitative figures presented below were measured from a real system; they are constructed to be representative of patterns the cited literature reports and are labeled as estimates throughout.

DEVELOPMENT OF THE TIDE ARCHITECTURE

TIDE is organized around a connectivity-state machine with four states, each governing a distinct synchronization behavior.

Online & Synced. The mobile client has connectivity and no unsynchronized local changes; reads and writes pass through to the backend directly, following the always-online assumption much enterprise integration architecture already makes.

Local Write, Queued. A write occurs while the client lacks connectivity, or while the client's synchronization layer has chosen to queue it locally for batching; the write is recorded as a delta against the client's last-known-synced baseline, following [1] logging approach, rather than blocking the user interface until connectivity returns.

Reconnecting. Connectivity returns and the client begins transmitting its queued deltas; for data types mapped onto a conflict-free replicated data type[4], the backend merges the delta automatically, while for other data types the delta is checked against the backend's current state for a conflict following Bayou-style dependency checking[2].

Delta Merge & Conflict Resolution. Where a conflict is detected, TIDE applies a per-data-type resolution policy, selected at design time for each data type based on its merge semantics, rather than a single uniform policy applied across the entire application's data model.

CONSTRUCTION OF THE EVALUATION SCENARIO

To TIDE's reasoning, this paper constructs a disguised enterprise field-service scenario, assembled from patterns reported across the cited disconnected-operation and mobile-cloud

literature rather than drawn from a specific company's application. The scenario follows a field technician whose mobile application records equipment inspection results, updates an inventory count of parts used, and schedules a follow-up visit, often while working in locations with no cellular or Wi-Fi connectivity. This scenario is intentionally small enough to render as a complete connectivity-state diagram while remaining large enough to exhibit both conflict-free data types, the parts-used inventory count, and conflict-prone data types, the follow-up visit scheduling, within a single session.

QUANTITATIVE ESTIMATES

Because no production measurement data accompanies this scenario, every quantitative figure presented in the Results section, including synchronization data volume, conflict rates, and reconciliation time, is explicitly labeled an estimate. These figures are constructed to be directionally consistent with the patterns [2] and [4] report, not as a substitute for empirical measurement of any specific system.

SCOPE AND ASSUMPTIONS

TIDE is scoped to enterprise mobile applications whose data model can be decomposed into distinct data types each amenable to an explicit merge-policy decision, an assumption that holds reasonably well for the structured, record-oriented data common in field-service, inventory, and sales-tracking applications but less comfortably for applications centered on large, unstructured content such as media files, where delta-based synchronization at the field level is not meaningful. TIDE assumes the backend itself provides the durability and availability guarantees the classical literature assumes beneath a disconnected-operation client[1] and does not itself specify that layer.

VALIDITY CONSIDERATIONS

Two threats to the usefulness of the scenario deserve explicit acknowledgment. First, because the field-service scenario is constructed rather than observed, any numeric pattern it exhibits is a demonstration of TIDE's intended reasoning rather than evidence that the reasoning holds under a real enterprise's specific connectivity patterns and data model; the construction was deliberately kept consistent with directional findings in [22-44], but consistency with prior findings is not independent confirmation of them. Second, a two-data-type scenario is small enough to be fully legible in a single connectivity-state diagram but correspondingly smaller than many enterprise mobile applications' full data models, which may involve dozens of distinct record types each requiring its own merge-policy decision; the scenario should be read as the state-machine mechanism TIDE applies, not as a claim about how straightforward the per-data-type policy-assignment process remains at that larger scale.

RESULTS

ARCHITECTURE OVERVIEW

Figure 1 renders the field-service scenario as a connectivity-state diagram: four states arranged around a cycle, labeled transition arrows showing what triggers each state change, and a small inset showing the two data types in the scenario, parts-used inventory count and follow-up visit scheduling, routed through different merge-policy paths once the Reconnecting state is reached.

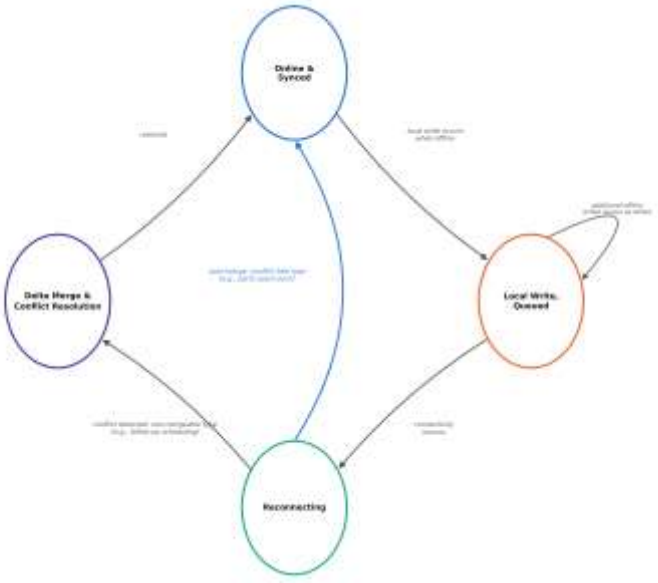


Figure 1. TIDE's connectivity-state machine, showing delta-based synchronization and per-data-type merge routing for an enterprise field-service scenario.

Table 1. comparison of mobile-cloud integration architectures.

Dimension	**Always-Online Design**	**Naive Full-Resync Design**	**TIDE-Guided Design**
Behavior during disconnection	Writes blocked or lost	Local writes allowed but untracked	Writes logged as deltas against last-synced baseline
Data transferred at reconnection	Not applicable; no queued state	Entire local dataset re-uploaded	Only the queued deltas
Conflict handling	Not applicable; no concurrent offline writes	Last writer wins, uniformly applied	Per-data-type policy, including conflict-free merge where applicable
User experience during disconnection	Application unusable or degraded	Application usable but changes are fragile	Application fully usable; changes durable and trackable

CASE SCENARIO

Consider the field technician's inspection visit when cellular connectivity drops immediately after arriving on site. Under an always-online design, the application either refuses to record the inspection until connectivity returns, forcing the technician to re-enter data later from memory, or silently fails to save the entry. Under a naive full-resync design, the application allows the technician to continue working, but when connectivity returns, the entire local dataset, not just the technician's new entries, is re-uploaded and compared against the backend, a slow operation that also risks a uniform last-writer-wins policy silently overwriting a colleague's concurrent inventory update made from a different device while the technician was

offline. Under TIDE, the technician's inspection result, parts-used count, and follow-up scheduling request are each logged as a delta the moment they are entered; when connectivity returns, the parts-used count, mapped onto a conflict-free replicated counter, merges automatically with any concurrent updates from other technicians, while the follow-up scheduling request, which cannot be merged automatically because two technicians might have proposed conflicting visit times, is flagged for the dispatching system to resolve explicitly.

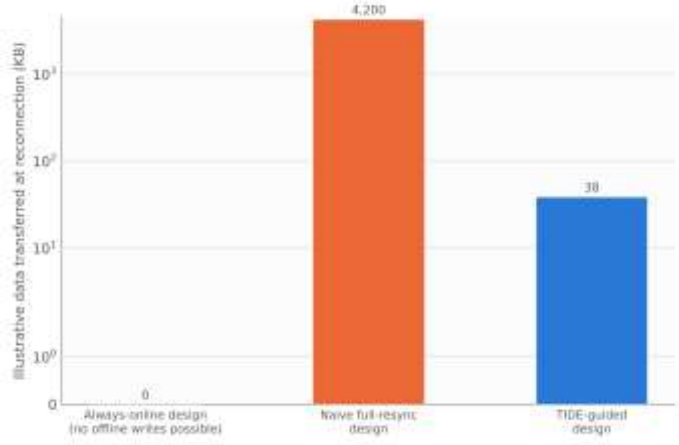


Figure 2. estimate of data transferred at reconnection under each design for the scenario described above, synthesized to demonstrate that TIDE's delta-based transfer avoids the disproportionate synchronization cost a naive full-resync design pays for a session in which only a small fraction of the technician's local dataset actually changed.

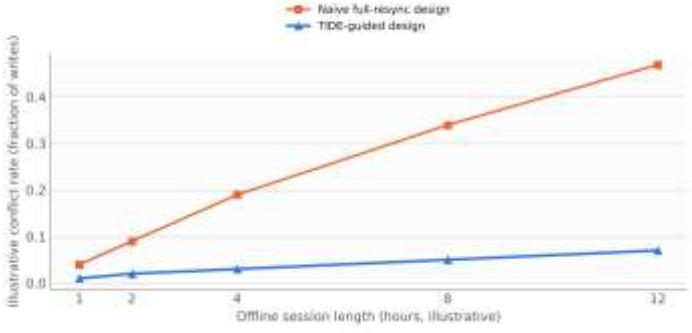


Figure 3. conflict rate across offline session lengths for the naive full-resync and TIDE-guided designs, synthesized to demonstrate that the gap between the two designs widens as offline session length grows.

DISCUSSION

IMPLICATIONS

The evidence assembled here, read alongside Terry *et al.*'s[2] and Shapiro *et al.*'s[4] findings, suggests that enterprise mobile-cloud integration architectures gain more from routing different data types through different, deliberately chosen merge policies than from applying a single synchronization strategy uniformly across an application's entire data model. This has a practical implication for enterprise mobile-application design: identifying, early in an application's data modeling, which fields are amenable to conflict-free merge and which require explicit conflict handling is a comparatively low-cost design-time decision that substantially reduces both synchronization cost and the user-visible disruption of merge conflicts, relative to treating the choice as an afterthought handled uniformly once synchronization problems are already being reported by users in the field.

This has a second implication specific to how enterprises prioritize mobile-application engineering investment. Organizations that treat synchronization as a generic platform concern, solved once by a single synchronization library applied uniformly across an application, tend to under-invest in the per-data-type merge-policy analysis the Case Scenario subsection , since that analysis requires domain knowledge about which fields genuinely tolerate automatic merging that a generic synchronization platform cannot supply on its own. The conflict-rate estimates in Figure 3, while , suggest that this gap widens as session length grows, implying that the benefit of deliberate per-data-type policy assignment should matter more, not less, for the extended offline sessions, a full day in the field rather than a brief elevator ride through a dead zone, that enterprise field-service and logistics applications are routinely designed to support.

This has a third, more operational implication for how an enterprise mobile team sequences its own adoption of per-data-type policy assignment, rather than treating it as a single all-at-once redesign. The Limitations subsection below notes that a field's eligibility for conflict-free merge depends on whether its correctness is fully determined by its own value or instead depends on a relationship with another field; this distinction gives a team a natural, low-risk starting order: fields whose independence from other fields is already clear from the data model, such as the parts-used inventory count in the Case Scenario subsection, can be assigned a conflict-free merge policy first, with comparatively little risk of a silently incorrect merge, while fields whose correctness plausibly depends on another field, such as the follow-up visit scheduling in the same scenario, are left under explicit Bayou-style reconciliation until that dependency has been examined carefully. Sequencing the work this way lets a team realize part of TIDE's synchronization-cost and conflict-rate benefit immediately, on the subset of the data model where the classification is least ambiguous, rather than deferring any benefit until every field in the application has been individually audited.

Figure 4 summarizes this classification question as a simple decision sequence a data modeler can apply field by field: whether the field's correctness depends on a relationship to another field, and, if not, whether an existing conflict-free replicated data type already covers its merge semantics. The figure is an interpretive aid built to organize the reasoning above, not a new empirical finding.

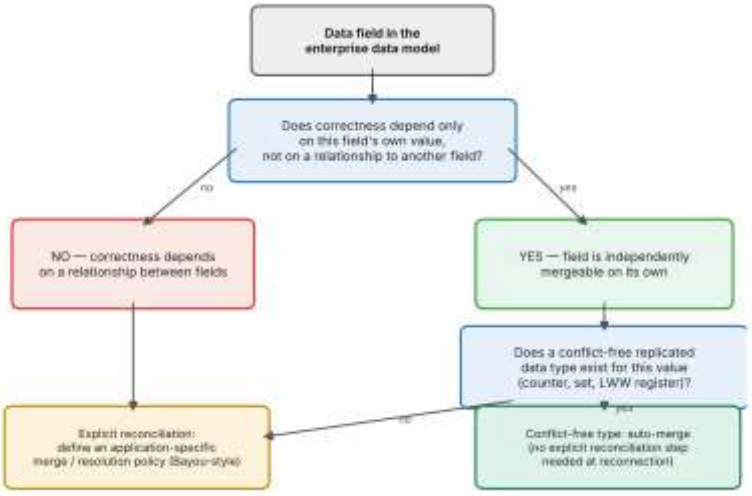


Figure 4. decision sequence for classifying a data field as conflict-free-mergeable versus requiring explicit Bayou-style reconciliation, synthesized to organize the per-data-type sequencing argument above rather than to report a measured classification outcome.

LIMITATIONS

TIDE's per-data-type policy selection does not eliminate the need for careful data modeling; a field incorrectly judged safe for conflict-free merge, because its true correctness constraints depend on a relationship with another field rather than being independently mergeable, can produce a result that merges cleanly but is nonetheless wrong, a risk the conflict-free replication literature itself acknowledges as a limit of the approach rather than a guarantee that merging is always semantically correct. The framework also assumes connectivity state can be detected reliably enough to trigger the correct state transition, an assumption that holds reasonably well for the extended disconnections typical of field-service work but less comfortably for the brief, flickering connectivity common in some mobile settings, where frequent state oscillation could itself become a source of synchronization overhead; a client that repeatedly toggles between the Reconnecting and Local Write, Queued states during a few seconds of intermittent signal gains little from TIDE's merge-routing logic and instead accumulates the overhead of repeatedly re-evaluating connectivity state without a stable window in which to complete it.

FUTURE RESEARCH

Future work should test whether per-data-type merge-policy selection, applied to a real enterprise mobile application's full data model rather than the two-data-type scenario in the Results section, actually reduces measured conflict rates and synchronization cost by margins comparable to the estimates presented here. A further direction is extending TIDE's connectivity-state machine to account for the flickering-connectivity case the Limitations subsection identifies as a limitation, potentially through a hysteresis mechanism that avoids triggering a full state transition for very brief connectivity changes.

CONCLUSION

This paper has argued that enterprise mobile-cloud integration architectures benefit from treating connectivity state as a first-class part of the integration design and from routing different data types through deliberately chosen, rather than uniform, conflict-resolution policies. Building on Kistler and Satyanarayanan's[1] disconnected-operation pattern, Terry *et al.*'s[2] weakly connected reconciliation approach, and Shapiro *et al.*'s[4] conflict-free replicated data types, this paper has proposed TIDE, its connectivity-state machine and delta-based synchronization mechanism through a disguised field-service scenario, and compared it, through estimates explicitly labeled as such, against an always-online design and a naive full-resync design on dimensions tied to data transfer cost and conflict rate. The central claim is not that any particular conflict-rate figure is representative, but that deliberately matching each data type to its appropriate merge policy, rather than synchronizing an entire application uniformly, is itself the primary lever available to enterprise organizations seeking to integrate mobile computing with cloud-based information systems reliably under intermittent connectivity.

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