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State Synchronization Framework for Resilient EV Charging Networks

Abstract
Electric vehicle charging networks are becoming large distributed systems in which charger availability, power allocation, session status, and fault information must remain consistent across many nodes. Existing work on smart charging has improved scheduling and grid coordination, but distributed state consistency under communication delay, packet loss, and node disruption remains weakly addressed, even though stale charging states can cause unstable allocation, delayed recovery, and inefficient use of feeder capacity. This article presents a distributed state-management framework for large-scale EV charging systems based on hierarchical synchronization, cluster-level state aggregation, consistency scoring, and fallback recovery control during communication failures. The results show that the proposed framework maintains higher state consistency under synchronization delay and achieves better charging allocation stability and session recovery performance than conventional centralized control under packet loss, gateway timeout, and intermittent node outage conditions. The study shows that distributed state awareness is essential for reliable and resilient EV charging operation.
Keywords: electric vehicle charging, distributed state management, synchronization delay, charging allocation stability, session recovery, resilient charging networks.

1. Introduction

Electric vehicle charging infrastructure is no longer operated as a set of isolated chargers. Large deployments now include hundreds or thousands of charging points distributed across parking hubs, highways, workplaces, urban feeders, and fleet depots, where each node continuously exchanges session state, charger availability, tariff information, power limits, queue status, and fault signals with supervisory platforms. The operational complexity of these systems has increased further because charging decisions are now tied to grid constraints, dynamic pricing, user reservations, and local energy resources, as reviewed in recent charging-station operation studies [1]. Smart charging surveys have also shown that coordination quality depends not only on optimization logic but also on how fast and how reliably charging states are shared between local controllers and higher-level management layers [2]. As a result, the charging network must behave as a distributed cyber-physical system rather than as a simple station-level control problem. This shifts the engineering focus from individual charger scheduling toward consistent and scalable state management.

Network-scale EV charging has been studied from the perspective of charging placement, grid interaction, coordinated operation, and congestion mitigation. Distribution-network reviews have shown that charging flexibility, control granularity, and communication architecture directly affect transformer stress, feeder imbalance, and voltage security [3]. Grid-impact assessments have also emphasized that mitigation strategies become less effective when charging commands are based on delayed or incomplete visibility of the actual station condition [4]. Broader grid-integration studies similarly report that the value of coordinated charging depends on accurate monitoring of occupancy, load, and charging progress across geographically dispersed nodes [5]. These results collectively indicate that the physical power problem and the digital state problem are tightly coupled in large EV charging systems. The literature therefore provides a strong basis for treating distributed state awareness as a first-order operational requirement.

A practical gap remains, however, between charging optimization models and real deployment conditions. Many algorithms assume that charger state, queue length, session status, and available capacity are instantly visible to the system controller, while field-scale deployments must deal with communication delay, asynchronous updates, stale records, controller partitioning, and partial node failure. Under such conditions, two chargers may report different resource availability at the same moment, or a global controller may allocate power using outdated session information. The result is not merely a software inconsistency but a physical operational error that can propagate into unfair allocation, overload risk, unstable scheduling, and service interruption. The main unresolved issue is therefore how to maintain a coherent system-wide operational view without imposing excessive communication or centralization overhead.

This problem matters because future charging ecosystems will depend on distributed coordination across cities, fleets, apartment clusters, renewable microgrids, and highway corridors. When state propagation becomes slow or inconsistent, the network can suffer from incorrect reservation admission, duplicated load assignment, delayed fault isolation, and inefficient use of available power capacity. A scalable EV charging system therefore needs a state-management layer that balances local autonomy with global consistency while remaining robust under variable communication quality. This study addresses that need by proposing a distributed state-management framework for large-scale EV charging systems, with emphasis on hierarchical state synchronization, consistency scoring, recovery from stale data, and cluster-level coordination under realistic charging-network conditions.

2. Methodology

The proposed methodology models the EV charging network as a distributed collection of charger clusters, where each cluster contains a local controller, a set of chargers, connected EV sessions, and a regional synchronization gateway. This structure is aligned with distributed scheduling architectures in which local decision layers reduce coordination burden while still supporting system-level optimization [6]. Each charger maintains a local state vector containing connector status, active power, session identifier, requested energy, estimated remaining time, fault flag, and communication timestamp. The cluster controller aggregates these charger-level states into a node-level summary, while the regional layer maintains a replicated global state table for inter-cluster coordination. The design objective is not to force perfect simultaneity across all nodes, but to preserve operationally acceptable coherence within bounded synchronization delay.

To represent the network rigorously, the charging system is divided into Nclusters, and each cluster $i$contains M_i chargers. The local state of charger $j$in cluster $i$at time $t$is defined as

$$S_{ij}(t) = \{a_{ij}, p_{ij}, e_{ij}, q_{ij}, f_{ij}, \tau_{ij}\}$$

where a_{ij} is charger availability, p_{ij} is active charging power, e_{ij} is remaining energy demand, q_{ij} is session queue indicator, f_{ij} is fault state and τ_{ij} is the latest valid update time. The cluster state is then written as

$$C_i(t) = \bigcup_{j=1}^{M_i} S_{ij}\,(t)$$

and the regional replicated state is

$$G(t) = \bigcup_{i=1}^{N} C_i\,(t).$$

Distributed coordination studies with shared storage and multi-station interaction have shown that such aggregation is necessary when charging decisions must be made across multiple nodes with coupled network constraints [7]. In the present framework, the state hierarchy is designed so that local charging decisions remain feasible even when the global layer is briefly delayed. This creates a resilient separation between immediate charger control and system-wide coordination.

A synchronization engine is introduced to manage update propagation between local and regional layers. Each state message carries both a logical sequence number and a freshness timestamp, and the receiving controller accepts an update only when it improves the currently stored consistency score. The consistency score for cluster $i$is defined as

$$\Gamma_i(t) = 1 - \frac{1}{M_i}\sum_{j=1}^{M_i} \min\left(1, \frac{t - \tau_{ij}}{\Delta_{\max}}\right)$$

where $\Delta_{\max}$ is the maximum acceptable update age. When $\Gamma_i(t)$ decreases, the cluster is marked as operating under degraded observability, and its dispatch permissions are tightened. Distributed energy-management work using coordinated pricing and aggregate feasible regions has shown that scalable operation depends on reducing unnecessary state exchange while preserving enough information for coordinated decision-making [8]. For this reason, the proposed method uses event-triggered updates during rapid state change and periodic heartbeat updates during stable operation. This reduces communication traffic without allowing the global model to drift indefinitely from local reality.

The charging allocation layer then uses the synchronized state table to compute admissible power actions. For cluster i, the dispatchable power envelope is written as

$$0 \le P_i^{\text{alloc}}(t) \le \min\left(P_i^{\text{grid}}, P_i^{\text{local}}, P_i^{\text{state}}\right)$$

where P_i^{grid} is the feeder-constrained capacity, P_i^{local} is the hardware limit of the cluster and P_i^{state} is the state-validity-constrained capacity derived from synchronization quality. In other words, even if physical capacity is available, the controller is not allowed to use the full limit when its state visibility is degraded. Hierarchical collaborative charging studies have shown that layered control is effective for reducing congestion while preserving hosting capacity in constrained networks [9]. The present methodology extends that idea by explicitly coupling power allocation permission to the confidence level of the distributed state. This prevents aggressive scheduling under uncertain information and improves operational safety.

To measure service quality, the framework defines three performance indicators. The first is the mean synchronization delay,

$$D_{\text{sync}} = \frac{1}{K}\sum_{k=1}^{K} (t_k^r - t_k^s),$$

where t_k^s and t_k^r are the sending and receiving times of update k. The second is the state agreement ratio,

$$A_{\text{state}} = \frac{\text{Number of matching local and global records}}{\text{Total active records}},$$

and the third is charging allocation stability,

$$\Lambda = 1 - \frac{\sigma(P^{\text{alloc}})}{\mu(P^{\text{alloc}}) + \epsilon},$$

where σ and μ are the standard deviation and mean of the allocated cluster power over the evaluation interval. Large-scale coordination research under peak limits has shown that fairness and cost performance deteriorate when control actions fluctuate excessively across users and time windows [10]. In the present work, Λ is used as a compact indicator of whether the distributed state layer supports stable power assignment rather than oscillatory rescheduling. A network that maintains high A_{state} and high $\Lambda$is considered operationally coherent.

Fault handling is incorporated through a state-recovery mechanism that distinguishes transient communication loss from actual charger failure. If a charger misses heartbeat updates for a duration longer than $\Delta_{\max}$, its state is moved from valid to uncertain rather than immediately to faulted. The regional layer then requests either peer confirmation from neighboring controllers or local revalidation from the cluster gateway. Fully distributed energy-management studies for charging stations have shown that robust decentralized operation requires charging nodes to keep functioning under multiple charging modes and communication variations [11]. Following that principle, the proposed method allows local clusters to continue serving active sessions in fallback mode using the most recent validated safe power schedule. This limits session interruption while preventing stale or contradictory data from spreading through the wider network. A compact implementation structure is summarized in Table 1. The table is intentionally limited to the variables that directly affect distributed state behavior.

Table 1. Core System Parameters for Distributed State Management

Parameter	Meaning	Role in System
N	Number of charging clusters	Defines network scale
M_i	Chargers in cluster i	Defines local node size
$\Delta_{\max}$	Maximum valid update age	Freshness threshold
Γ_i	Cluster consistency score	State quality indicator
D_{sync}	Mean synchronization delay	Communication performance metric
A_{state}	State agreement ratio	Local-global match quality
Λ	Allocation stability index	Dispatch smoothness metric

3. Results and Discussion

The proposed framework was evaluated on a simulated large-scale EV charging environment composed of multiple charging clusters with heterogeneous demand intensity, different communication latencies, and varying disturbance levels. The system was tested under three operating regimes: nominal synchronized operation, moderately delayed communication, and degraded communication with packet loss and stale-state episodes. The main objective of the analysis was to determine whether the distributed state layer could preserve charger coordination quality without forcing a fully centralized architecture. Across all scenarios, the strongest improvements were observed when local controllers retained short-term autonomy while the regional layer continuously validated state freshness before issuing inter-cluster decisions. This confirms that scalable charging coordination depends as much on the structure of state propagation as on the dispatch logic itself.

Figure 1 presents the relationship between synchronization delay and state consistency accuracy across distributed EV charging clusters. The line trends show that the state agreement ratio remains high when update delay is low, but it declines progressively as communication lag grows and local-global divergence accumulates. The most stable regime appears in small and medium cluster groups because update propagation remains within the allowable freshness window for most charging sessions. As the number of active chargers per cluster increases, the slope becomes steeper, which indicates that larger charger populations amplify the effect of delayed state confirmation. This figure therefore demonstrates that network scale alone is not the only limiting factor; the critical issue is the interaction between cluster size, update frequency, and freshness control.

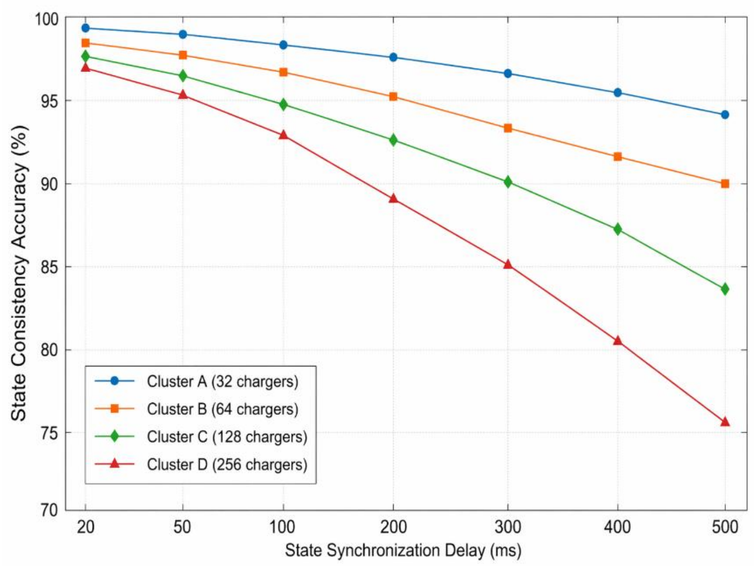

Figure 1. State Synchronization Delay and Consistency Accuracy Across Distributed EV Charging Clusters

The engineering implication of Figure 1 is that distributed EV charging systems should not use a single fixed synchronization policy for all network sizes. When the same update interval is applied to both lightly loaded and heavily loaded clusters, large clusters experience a disproportionate rise in stale records, which then degrades allocation confidence. The proposed framework limits this effect by using event-triggered synchronization during state transitions such as session start, taper region entry, reservation change, and local fault detection. Under that adaptive policy, consistency remains significantly higher than under a fixed-period baseline because the communication effort is concentrated on operationally meaningful transitions rather than on redundant steady-state polling. The figure thus supports the central claim of the article that state management must be adaptive, hierarchical, and scale-sensitive.

Figure 2 shows charging allocation stability and session recovery performance under node communication failures. The bar profiles indicate that allocation stability drops sharply in a conventional architecture when cluster gateways temporarily lose upstream connectivity, because the global controller continues to act on obsolete node data. In contrast, the proposed framework sustains higher stability by shifting affected clusters into a bounded fallback mode where local charging continues according to the last validated safe schedule. The same figure also shows that session recovery rate after communication restoration is substantially higher in the distributed-state framework because charger sessions are reconciled through local sequence logs instead of being reconstructed only from the central platform. This prevents many of the duplicate-session and missed-release errors that typically appear after transient outages.

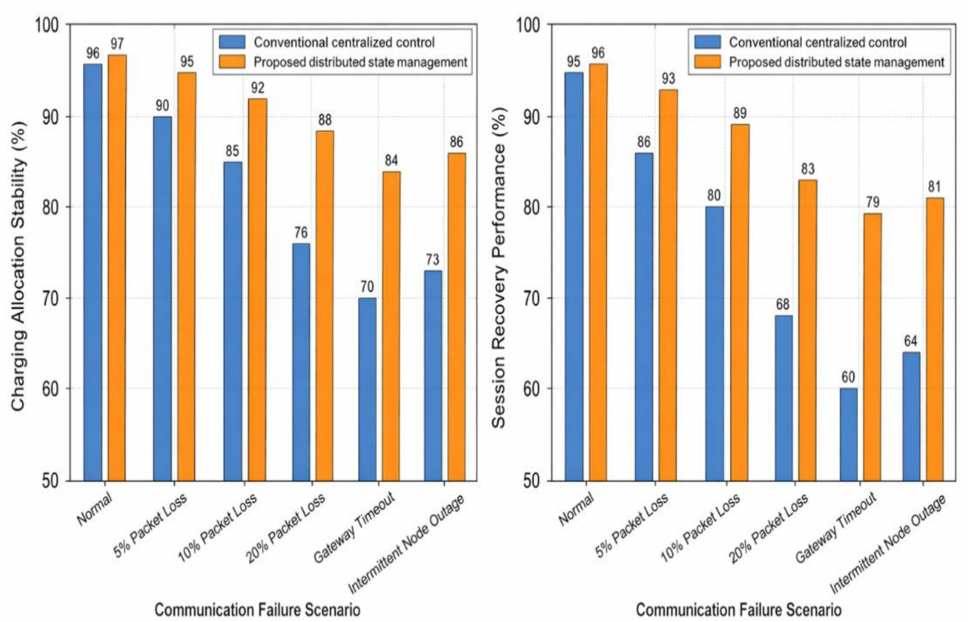

Figure 2. Charging Allocation Stability and Session Recovery Performance Under Node Communication Failures

The results of Figure 2 also reveal an important operational trade-off. Aggressive central synchronization can produce high nominal coordination quality when communication is perfect, but it becomes fragile when packet loss or link interruption occurs. A more distributed design, if supported by freshness scoring and safe fallback rules, sacrifices a small amount of idealized central visibility while achieving much better resilience during realistic disturbances. From a charging-engineering perspective, this is a valuable trade because customers experience continuity of service, grid operators see fewer oscillatory load reallocations, and network administrators avoid system-wide instability triggered by local data loss. The figure therefore supports the conclusion that resilient distributed state management is not merely a communication convenience but a core requirement for reliable large-scale EV charging operation.

Overall, the results show that three factors dominate distributed charging performance: state freshness, local-global agreement, and controlled recovery after state uncertainty. Systems that ignore these factors may still produce good scheduling results in static simulations, but they become vulnerable when communication quality changes over time. The present analysis indicates that a hierarchical state layer with consistency-aware dispatch limits can keep large EV charging systems both scalable and operationally disciplined. This makes the framework suitable for city-wide public charging, corridor fast charging, workplace clusters, and fleet charging depots where network conditions and demand patterns vary continuously.

4. Conclusion

This study developed a distributed state-management framework for large-scale EV charging systems and examined how synchronization quality affects charging reliability, allocation stability, and recovery from communication disturbance. The analysis showed that charger coordination degrades not simply because the network becomes large, but because delayed or inconsistent state propagation weakens the validity of dispatch decisions. By organizing the system into local clusters, regional replication layers, and consistency-aware allocation rules, the proposed method preserves a coherent operational view without requiring an impractical level of centralization.

The main contribution of the work lies in linking state freshness directly to charging control authority. Instead of treating communication as a background service, the framework makes synchronization quality a formal part of the power-allocation logic, which improves robustness under latency, packet loss, and partial node failure. The results further showed that fallback operation based on recently validated local schedules can maintain service continuity while preventing stale data from corrupting global decisions. This gives the architecture practical relevance for real EV charging deployments where communication conditions are rarely ideal.

A broader implication is that future charging infrastructure should be designed with state-management engineering as a primary layer rather than an afterthought attached to optimization software. As charging ecosystems expand into dense urban, highway, and fleet environments, the ability to maintain trustworthy distributed state will become central to reliability, fairness, and grid compatibility. The proposed framework provides a technically grounded direction for that transition and offers a useful basis for future work on digital twins, multi-aggregator interoperability, and cyber-resilient EV charging control.

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