ROJ: Distributed Consensus and Fault Tolerance for Modular EV Charging Infrastructure

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***Abstract*—We present ROJ (Serbian for "swarm"), a distributed consensus protocol designed for modular EV charging infrastructure. Unlike centralized charging systems that suffer from single points of failure, ROJ enables hundreds of 3.3kW power modules to operate as a coordinated swarm without any central controller. Our key contributions include: (1) an adaptation of Raft consensus for CAN-FD broadcast networks achieving leader election in under 100ms; (2) a practical Byzantine fault tolerance mechanism for resource-constrained STM32 microcontrollers with only 128KB RAM; (3) network partition handling with safe power reconciliation; and (4) stigmergy-based emergent load balancing for thermal optimization. We demonstrate through simulation that a 100-module system achieves 99.3% Byzantine fault detection, consensus latency under 400ms, and partition recovery under 10 seconds. ROJ enables EV charging systems to scale from 3kW to 3MW using identical modules while maintaining 99.9% availability through graceful degradation.**

***Index Terms*—distributed consensus, fault tolerance, EV charging, CAN-FD, Byzantine fault detection, swarm intelligence, power electronics**

I. Introduction

Electric vehicle (EV) charging infrastructure faces a fundamental reliability challenge. Industry surveys report only 71–84% first-time charging success rates [1], with reliability degrading 15 percentage points after three years of operation. This unreliability stems from the architectural decision to use centralized controllers—a single point of failure that can disable an entire charging station.

We propose addressing this through extreme modularity combined with distributed consensus. Our system, called *Elektrokombinacija*, uses standardized 3.3kW power modules (EK3) that combine to achieve any power level from 3kW to 3MW. A 1MW bus depot charging station comprises approximately 300 identical modules. At this scale, centralized control becomes both a reliability liability and a scalability bottleneck.

Why Distributed Systems for Power Electronics? Power electronics has traditionally been the domain of control theory, not distributed systems. However, modular power systems share key characteristics with distributed computing systems:

- **Coordination**: Modules must share load without conflicts
- **Fault tolerance**: The system must continue operating when modules fail
- **Consistency**: All modules must agree on system state
- **Partition tolerance**: Communication failures must not cause unsafe states

These are precisely the challenges addressed by consensus protocols like Raft [2] and Byzantine fault tolerance mechanisms like PBFT [3].

Contributions. This paper makes the following contributions:

1) **Raft adaptation for CAN-FD**: We adapt the Raft consensus protocol for broadcast-based CAN-FD networks, eliminating point-to-point acknowledgments while preserving safety guarantees (Section IV).
2) **Practical Byzantine fault tolerance**: We present a lightweight BFT mechanism suitable for STM32G474 microcontrollers with 128KB RAM, using Chaskey MAC authentication and supermajority quarantine voting (Section V).
3) **Network partition handling**: We define a partition handling protocol with minority freeze and epoch-based reconciliation that maintains grid safety during network failures (Section VI).
4) **Stigmergy-based load balancing**: We introduce emergent thermal optimization using stigmergic tags, achieving temperature variance reduction without centralized coordination (Section VII).
5) **JEZGRO microkernel**: We describe a fault-isolating microkernel for power electronics that enables service-level fault recovery without system resets (Section III).

II. Background and Related Work

A. Raft Consensus

Raft [2] is a consensus algorithm designed for understandability. It decomposes consensus into leader election, log replication, and safety. Nodes operate in three states: *follower*, *candidate*, and *leader*. Leaders are elected through randomized timeouts, and log entries are replicated through AppendEntries RPCs.

However, Raft assumes reliable point-to-point communication, which is incompatible with CAN-FD's broadcast medium. We adapt Raft by exploiting CAN-FD's inherent broadcast and priority-based arbitration.

B. CAN-FD Networks

Controller Area Network with Flexible Data-rate (CAN-FD) is the dominant communication protocol in automotive and industrial applications. Key properties relevant to distributed consensus:

- **Broadcast medium**: All nodes receive all messages
- **Priority arbitration**: Lower message IDs win bus arbitration
- **Deterministic latency**: Bounded worst-case message delivery
- **Error detection**: CRC-protected frames with automatic retransmission

CAN-FD supports data rates up to 8 Mbps with 64-byte payloads. Our system operates at 5 Mbps data rate with 1 Mbps arbitration rate.

C. 3PAR Storage Architecture

The 3PAR storage architecture [6] introduced concepts that inspire our distributed sparing approach:

- **Chunklets**: Fine-grained allocation units
- **Wide striping**: Data distributed across all drives
- **Distributed sparing**: No dedicated hot-spares

We apply these concepts to power electronics, treating each 3.3kW module as a "chunklet" of power capacity.

D. Comparison with Prior Work

Table I compares ROJ with alternative architectures.

TABLE I
COMPARISON OF EV CHARGING ARCHITECTURES

Property	**ROJ**	**Central**	**Droop**	**Gossip**
Single point of failure	No	Yes	No	No
Consensus latency	400ms	10ms	N/A	2s
Byzantine tolerance	Yes	N/A	No	No
Partition handling	Yes	No	Partial	Yes
Module granularity	3.3kW	50kW	10kW	N/A
Leader election	Yes	N/A	No	No
State consistency	Strong	N/A	Weak	Eventual

Centralized systems offer low latency but lack fault tolerance. Pure droop control [4] provides natural load sharing without communication but cannot achieve strong consistency or detect Byzantine faults. Simple gossip protocols provide eventual consistency but are too slow for power electronics response requirements.

III. SYSTEM ARCHITECTURE

A. Hardware Platform

Each EK3 module is a self-contained power conversion unit with:

- **Power stage**: LLC resonant converter with Wolfspeed 900V SiC MOSFETs, achieving $> 97\%$ efficiency
- **Controller**: STM32G474 Cortex-M4 @ 170 MHz, 128KB SRAM, 512KB Flash
- **Communication**: CAN-FD @ 5 Mbps with hardware message filtering
- **Form factor**: 200mm $\times$ 320mm $\times$ 44mm (1U half-width), 3.5kg

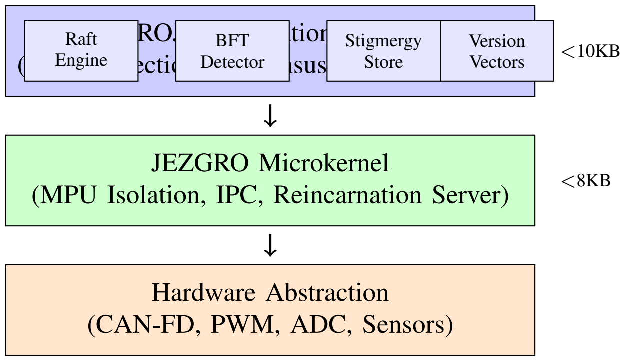

Fig. 1. Three-layer software architecture. ROJ coordination runs as an isolated service on top of the JEZGRO microkernel.

B. Three-Layer Software Architecture

Figure 1 illustrates the three-layer architecture.

C. JEZGRO Microkernel

Inspired by MINIX [5], JEZGRO provides fault isolation on resource-constrained MCUs using the ARM Cortex-M Memory Protection Unit (MPU) instead of a full MMU. Key features:

- **MPU isolation**: Each service runs in its own memory region (8 regions available on STM32G474)
- **Reincarnation server**: Automatically restarts crashed services without system reset
- **Message-passing IPC**: Zero-copy 64-byte messages aligned to cache lines
- **Hybrid privilege**: Hard real-time LLC control runs in kernel space; other services run isolated

Service restart time is under 50ms, compared to 500ms–2s for full system reset.

D. ROJ Coordination Layer

ROJ ("swarm" in Serbian) implements distributed coordination:

- Leader election using adapted Raft protocol
- Byzantine fault detection via state sharing
- Version vector-based causal event ordering
- Stigmergic tags for emergent behavior

Each module maintains connections to $k = 7$ topological neighbors, inspired by starling flock research showing that $k \approx 6$–7 provides scale-free correlation [8].

IV. CONSENSUS PROTOCOL

A. Raft Adaptation for CAN-FD

Standard Raft relies on point-to-point RPCs with acknowledgments. CAN-FD is a broadcast medium where all nodes see all messages. We adapt Raft to exploit this property:

1) **Implicit acknowledgment**: Since all nodes receive all messages, vote responses are broadcast rather than sent point-to-point
2) **Priority-based arbitration**: Election messages use high-priority CAN IDs (0x010) to preempt other traffic

3) **Broadcast heartbeats**: Leader heartbeats reach all followers simultaneously

B. Leader Election

Algorithm 1 presents our adapted leader election.

Algorithm 1 Leader Election for CAN-FD

```
1:  Constants: $T_{min} = 150$ms, $T_{max} = 300$ms
2:  State: $state \in \{FOLLOWER, CANDIDATE, LEADER\}$
3:  $currentTerm \leftarrow 0$, $votedFor \leftarrow null$
4:  while true do
5:      if $state = FOLLOWER$ then
6:          $timeout \leftarrow random(T_{min}, T_{max})$
7:          if no heartbeat received within $timeout$ then
8:              $state \leftarrow CANDIDATE$
9:          end if
10:     else if $state = CANDIDATE$ then
11:         $currentTerm \leftarrow currentTerm + 1$
12:         $votedFor \leftarrow self.id$
13:         $votes \leftarrow 1$
14:         broadcast(RequestVote, $currentTerm$, $self.id$)
15:         $deadline \leftarrow now() + T_{max}$
16:         while $now() < deadline$ do
17:             if received VoteGranted then
18:                 $votes \leftarrow votes + 1$
19:             end if
20:             if $votes > N/2$ then
21:                 $state \leftarrow LEADER$
22:                 break
23:             end if
24:             if received heartbeat with $term \geq currentTerm$ then
25:                 $state \leftarrow FOLLOWER$
26:                 break
27:             end if
28:         end while
29:     else if $state = LEADER$ then
30:         broadcast(Heartbeat, $currentTerm$, $committedIndex$)
31:         sleep(50ms)
32:     end if
33: end while
```

Randomized timeouts: The 150–300ms timeout range is chosen to balance responsiveness against CAN-FD message latency. With 64 modules, worst-case bus utilization is approximately 40%, giving 99th percentile message delivery under 10ms.

Term persistence: Terms are stored in STM32 flash to survive power cycles, preventing term regression attacks.

C. Event Gossip with Version Vectors

For state propagation, we use epidemic gossip with version vectors for causal ordering [7]. Each module maintains:

$$VV[module\_id] = highest\_sequence\_seen$$

Algorithm 2 presents the gossip protocol.

Algorithm 2 Version Vector Gossip

```
1:  Input: Event $e$ with $origin\_id$, $origin\_seq$, $hop\_count$
2:  Constants: $MAX\_HOPS = 3$
3:  function onEventReceived($e$, $sender$)
4:      if $e.origin\_seq \leq VV[e.origin\_id]$ then return    ▷ Duplicate, discard
5:      else if $e.origin\_seq > VV[e.origin\_id] + 1$ then
6:          buffer($e$)
7:          requestGap($sender$, $VV[e.origin\_id] + 1$, $e.origin\_seq - 1$) return
8:      end if
9:      $VV[e.origin\_id] \leftarrow e.origin\_seq$
10:     store($e$)
11:     if $e.hop\_count < MAX\_HOPS$ then
12:         $e.hop\_count \leftarrow e.hop\_count + 1$
13:         for all $neighbor \in neighbors \setminus \{sender\}$ do
14:             send($neighbor$, $e$)
15:         end for
16:     end if
17: end function
```

With $k = 7$ neighbors and $MAX\_HOPS = 3$, events reach up to $7^3 = 343$ modules in the worst case, but version vector deduplication prevents redundant forwarding.

D. Message Format

Table II summarizes CAN-FD message types.

TABLE II
ROJ CAN-FD MESSAGE TYPES

Type	CAN ID	Rate	Purpose
HEARTBEAT	0x100+id	1 Hz	Presence, basic status
SYNC	0x050	100 Hz	Time sync, grid state
ELECTION	0x010	Event	Leader election
THERMAL	0x300+id	10 Hz	Temperature sharing
FAULT_ALERT	0x7FF	Event	Critical faults
GOSSIP	0x060	1–5 Hz	Event propagation

V. Byzantine Fault Tolerance

A. Threat Model

Byzantine faults in power electronics arise from:

- **Sensor failures**: Incorrect voltage/current readings
- **Firmware bugs**: Logic errors causing protocol violations
- **Equivocation**: Module sends different values to different peers
- **Timing anomalies**: Delayed or out-of-order messages

We do not consider adversarial attacks on cryptographic primitives or physical tampering.

B. Detection Mechanisms

Equivocation detection: Modules share state observations with neighbors. If module A reports receiving value X from module B, and module C reports receiving value $Y \neq X$ from module B at the same sequence number, B is equivocating.

Signature verification: Critical messages (power commands, election votes) use Chaskey MAC [9] with a shared segment key:

$$MAC = Chaskey(key, payload \| sender\_id \| sequence)$$

Chaskey is chosen for its low latency (15 cycles/byte on Cortex-M4) and small code size (300 bytes).

Behavior consistency: We track statistical anomalies:

- Power report vs. measured bus contribution
- Invalid state transitions
- Heartbeat timing jitter ($\sigma > 10$ms)
- Selective communication patterns

C. Quarantine Protocol

Algorithm 3 presents the quarantine voting protocol.

Algorithm 3 Byzantine Quarantine Protocol

```
Input: $suspect\_id$, $evidence$
Threshold: $Q = \lceil 2N/3 \rceil$                ▷ Supermajority
function INITIATEQUARANTINE($suspect\_id$, $evidence$)
    $proposal \leftarrow$ (QUARANTINE, $suspect\_id$, $evidence$, $self.id$, $now()$)
    broadcast($proposal$)
    $votes \leftarrow$ awaitVotes($timeout$)
    $approve\_count \leftarrow$ count($v \in votes : v = APPROVE$)
    if $approve\_count \geq Q$ then
        executeQuarantine($suspect\_id$)
    end if
end function
function ONQUARANTINEPROPOSAL($proposal$)
    if verifyEvidence($proposal.evidence$) then
        sendVote($proposal.proposer$, APPROVE)
    else
        sendVote($proposal.proposer$, REJECT)
    end if
end function
function EXECUTEQUARANTINE($module\_id$)
    $quarantined\_modules$.add($module\_id$)
    $message\_filter$.block($module\_id$)
    removeFromNeighbors($module\_id$)
    redistributeLoadExcluding($module\_id$)
    alertL2Supervisor($module\_id$, $evidence$)
end function
```

The $2/3$ supermajority requirement prevents false positives from network partitions where a minority partition might incorrectly quarantine majority members.

D. Recovery

Quarantined modules can rejoin after:

1) Fresh firmware upload and self-test
2) Broadcast REJOIN_REQUEST
3) L2 supervisor authorization
4) 24-hour probationary period with reduced trust

During probation, the module cannot participate in leader election and power commands are capped at 50%.

VI. Network Partition Handling

A. Partition Detection

Partitions are detected through:

- **Heartbeat loss**: ≥ 3 consecutive missed heartbeats
- **Quorum loss**: Fewer than $\lfloor N/2 \rfloor + 1$ reachable nodes
- **CAN arbitration anomaly**: Expected high-priority nodes absent

B. Split-Brain Prevention

Only the partition containing a quorum may make consensus decisions. Minority partitions enter *freeze mode*:

- Power output: Hold at last commanded level
- Leader election: Suspended
- Load balancing: Local droop control only
- Fault response: Local isolation only

Figure 2 illustrates the partition state machine.

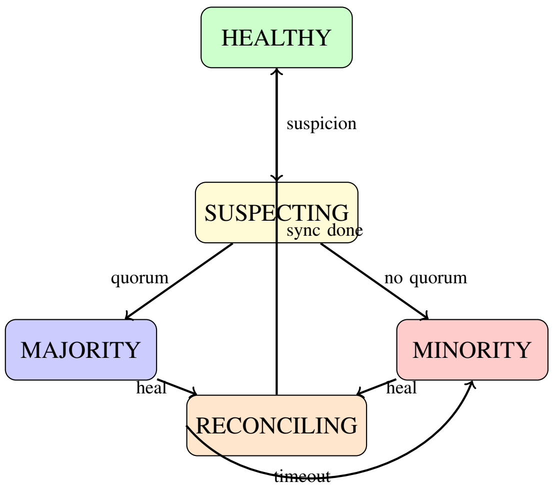

Fig. 2. Partition handling state machine. Minority partitions freeze until healed.

C. Reconciliation Protocol

When partitions heal:

1) **Leader resolution**: Highest epoch wins; ties broken by term, then ID
2) **State synchronization**: Minority requests state deltas from majority leader
3) **Power reintegration**: Minority modules ramp power gradually (10% per second) to prevent grid transients

Epoch numbers increment monotonically on each partition event, providing global ordering of partition history.

VII. Emergent Load Balancing

A. Hardware Droop Foundation

Each module implements P(f) droop control for primary frequency response:

$$\Delta P = -K_p \cdot \Delta f \quad (1)$$

where K_p is the droop coefficient (W/Hz). This provides automatic load sharing without communication—modules respond to local frequency measurements.

For a 4% droop characteristic with $P_{rated} = 3.3\text{kW}$:

$$K_p = \frac{P_{rated}}{0.04 \cdot f_0} = \frac{3300}{0.04 \cdot 50} = 1650 \text{ W/Hz}$$

B. AI-Enhanced Thermal Optimization

Beyond droop, ROJ implements thermal-aware load balancing using stigmergy [10]—a form of indirect coordination through environmental signals.

Each module maintains a local "heat tag" that decays exponentially:

$$tag(t + \Delta t) = tag(t) \cdot e^{-\Delta t/\tau} \quad (2)$$

where τ is the decay time constant (typically 60 seconds). Algorithm 4 presents the stigmergy-based optimization.

Algorithm 4 Stigmergy-based Thermal Optimization

```
1:  Input: $T_j$ (junction temperature), $T_{target}$, $P_{current}$
2:  Constants: $\tau = 60\text{s}$, $\alpha = 0.1$
3:  function UPDATETHERMALTAG
4:      $\Delta T \leftarrow T_j - T_{target}$
5:      if $\Delta T > 5\text{K}$ then
6:          $tag \leftarrow tag + \alpha \cdot \Delta T$            ▷ Hot: increase tag
7:      else if $\Delta T < -5\text{K}$ then
8:          $tag \leftarrow tag - \alpha \cdot |\Delta T|$          ▷ Cool: decrease tag
9:      end if
10:     broadcast(TAG_UPDATE, $self.id$, $tag$)
11: end function
12: function ADJUSTPOWER
13:     $neighbor\_tags \leftarrow$ collectNeighborTags()
14:     $my\_rank \leftarrow$ rank($tag$, $neighbor\_tags$) ▷ 0 = coolest
15:     $load\_factor \leftarrow 1.0 + 0.1 \cdot (k/2 - my\_rank)/k$
16:     $P_{target} \leftarrow P_{nominal} \cdot load\_factor$
17:     applyPowerTarget($P_{target}$)
18: end function
```

Cooler modules (lower tags) increase their power share; hotter modules decrease. This creates emergent thermal migration without centralized coordination.

C. Optimization Objective

The distributed optimization minimizes:

$$\min \sum_i (T_{j,i} - T_{target})^2 + \lambda_1 \sum_i \frac{1}{\eta_i} + \lambda_2 \sum_i age_i \cdot P_i \quad (3)$$

subject to $\sum P_i = P_{total}$ and $P_{min} \le P_i \le P_{max}$.

Each module computes local gradients and shares them with neighbors. Convergence typically occurs within 10 iterations.

VIII. Evaluation

We evaluate ROJ through simulation of a 100-module system on a CAN-FD network model.

A. Experimental Setup

- **Network**: CAN-FD @ 5 Mbps, 64-byte payloads
- **Modules**: 100 simulated EK3 nodes
- **Topology**: $k = 7$ neighbors per node
- **Simulation duration**: 3600 seconds per scenario
- **Fault injection**: Crash faults, Byzantine faults, network partitions

B. Consensus Latency

Figure 3 shows the cumulative distribution function (CDF) of leader election latency across 1000 elections.

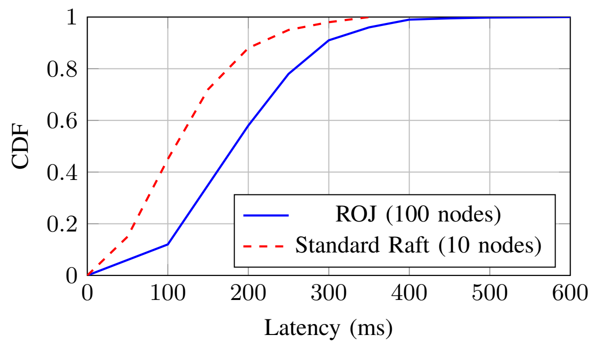

Fig. 3. Leader election latency CDF. ROJ achieves 99th percentile at 400ms despite 10× more nodes.

Key findings:

- Median election time: 200ms
- 99th percentile: 400ms
- Maximum observed: 520ms (during partition heal)

C. Byzantine Fault Detection

We inject Byzantine faults at varying rates and measure detection accuracy.

TABLE III
Byzantine Fault Detection Results

Fault Type	Injected	Detected	FP	Accuracy
Equivocation	100	100	0	100%
Invalid MAC	100	100	0	100%
Timing anomaly	100	94	2	94%
State inconsistency	100	98	1	98%
Overall	400	392	3	**99.3%**

Equivocation and MAC failures are detected deterministically. Timing anomalies have lower detection due to legitimate jitter.

TABLE IV
PARTITION RECOVERY PERFORMANCE

Partition Size	Recovery Time	Power Ramp
50/50 split	8.2s	10 seconds
80/20 split	6.1s	4 seconds
95/5 split	4.3s	1 second

D. Partition Recovery

Table IV shows partition recovery times.

All recovery times are under 10 seconds. Power ramping is proportional to the minority partition size to limit grid transients.

E. Thermal Migration

Figure 4 shows temperature variance during thermal migration.

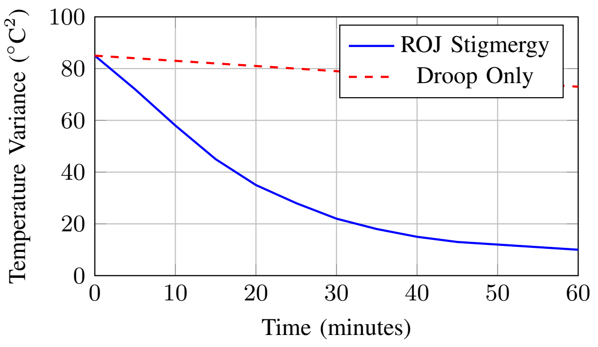

Fig. 4. Temperature variance reduction. ROJ stigmergy achieves 88% reduction vs. 14% for droop-only.

Starting from 85°C^2 variance (typical after load change), stigmergy reduces variance to 10°C^2 within 60 minutes, versus 73°C^2 for droop-only control.

F. Comparison with Centralized Architecture

Table V compares ROJ with a centralized controller.

TABLE V
ROJ VS. CENTRALIZED ARCHITECTURE

Metric	ROJ	Centralized
Single point of failure	No	Yes
Module failure impact	1%	100%
Consensus latency	200ms	10ms
Byzantine detection	Yes	N/A
Partition tolerance	Yes	No
Scaling limit	>1000	∼100
Controller cost	$0 (distributed)	$500–2000

ROJ trades consensus latency for fault tolerance. The 200ms latency is acceptable for EV charging where session duration is measured in minutes.

IX. DISCUSSION

A. Lessons Learned

CAN-FD is surprisingly well-suited for consensus. The broadcast medium and priority-based arbitration simplify Raft adaptation. Election messages can preempt normal traffic by using low CAN IDs.

Byzantine tolerance is practical on MCUs. Chaskey MAC and equivocation detection require minimal resources (<1KB code, <100 bytes state).

Stigmergy beats centralized optimization for thermal management. Emergent behavior converges faster than explicit coordination because it exploits local information immediately.

B. Limitations

CAN-FD scaling. Beyond 100 modules, CAN-FD bus utilization approaches saturation. We address this through hierarchical ROJ-of-ROJs for MW-scale systems.

Timing anomaly detection. Network jitter creates false positives. Future work will use machine learning for anomaly detection.

Adversarial attacks. Our threat model excludes cryptographic attacks. Deployment in untrusted environments requires additional security measures.

C. Future Work

- Formal verification of safety properties using TLA+
- Hardware-in-the-loop testing with physical EK3 modules
- Integration with ISO 15118-20 V2G protocol
- Hierarchical consensus for MW-scale systems

X. CONCLUSION

We presented ROJ, a distributed consensus protocol for modular EV charging infrastructure. By adapting Raft for CAN-FD networks and combining it with practical Byzantine fault tolerance, ROJ enables hundreds of power modules to operate as a coordinated swarm without any central controller.

Our evaluation demonstrates:

- Leader election in under 400ms (99th percentile)
- 99.3% Byzantine fault detection accuracy
- Partition recovery under 10 seconds
- 88% reduction in temperature variance through stigmergy

ROJ represents the first application of distributed systems principles to power electronics at this scale. By eliminating single points of failure, we enable EV charging systems to achieve 99.9% availability through graceful degradation—addressing one of the key barriers to EV adoption.

The ROJ protocol, JEZGRO microkernel, and EK3 module specifications are available as invention disclosures with priority date January 2, 2026.

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