How are agent communication protocols adapted and implemented for secure, scalable coordination in distributed energy resource maintenance?

Agent protocols achieve secure and scalable coordination through reinforcement learning, consensus-based techniques, and negotiation methods, while implementing encryption and hierarchical control structures.

Abstract

Agent communication protocols for distributed energy resource maintenance appear in 25 studies that describe secure, scalable coordination through distinct design choices. Fourteen studies employ distributed or decentralized multi-agent architectures—13 with distributed protocols and 8 with decentralized methods—to support tasks such as fault detection and restoration, self-healing, and economic dispatch. Sixteen studies validate approaches via simulation, while 5 report field or reference implementations.

Adaptation methods include reinforcement learning (reported in 4 studies), consensus- and leader election–based techniques (3 studies), and negotiation or rule-based approaches (2 studies each). Security features such as SSL, VPN, and TLS encryption are integrated in 13 studies, with some emphasizing resilience against cyber-attacks and communication failures. Scalability is achieved by clustering, reduced communication overhead, hierarchical or layered control, and minimal data sharing. Collectively, the papers indicate that agent protocols adapted through these techniques can support secure, scalable maintenance of distributed energy resources.

Paper search

Using your research question "How are agent communication protocols adapted and implemented for secure, scalable coordination in distributed energy resource maintenance?", we searched across over 126 million academic papers from the Semantic Scholar corpus. We retrieved the 499 papers most relevant to the query.

Screening

We screened in papers that met these criteria:

- **DER System Focus**: Does the study focus on distributed energy resource (DER) systems AND include aspects of maintenance or system upkeep?
- **Multi-Agent Protocol**: Does the research investigate communication protocols involving multiple agents or systems (more than a single agent)?
- **Security and Scalability**: Does the study address either security mechanisms OR scalability aspects (or both) in its coordination protocol design?
- **Maintenance Coordination**: Does the study include specific details about maintenance coordination or scheduling processes?
- **Validation Method**: Does the study include empirical data, simulation results, OR validated theoretical frameworks?
- **Implementation Details**: Does the research provide technical implementation details of the proposed protocols or coordination mechanisms?
- **Practical Application**: Does the study demonstrate or discuss practical application of the coordination mechanisms in a DER context?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Data extraction

We asked a large language model to extract each data column below from each paper. We gave the model the extraction instructions shown below for each column.

- **Agent Communication Protocol Type**:

  Identify and describe the specific type of agent communication protocol used in the study. Look in the methods or technical approach sections for details about:

- Communication architecture (centralized, decentralized, distributed)
- Communication mechanism (direct neighbor communication, multi-hop communication, etc.)
- Key communication characteristics (autonomy, local view, scalability)

If multiple communication protocols are described, list all. If the protocol is not explicitly named, provide a detailed description of its key features. If no clear protocol is identified, write "Not specified".

- **Agent Characteristics and Capabilities**:

  Extract detailed information about the agents' characteristics from the methods section:

- Types of agents used (e.g., switch agents, energy storage agents, prosumer agents)
- Specific capabilities of each agent type
- Decision-making mechanisms (e.g., reinforcement learning, rule-based)
- Autonomy level and decision-making scope

List each agent type separately with its specific characteristics. If agent details are not clearly defined, note "Agent characteristics not fully specified".

- **Coordination Mechanism**:

  Identify how agents coordinate and interact to achieve system objectives:

- Coordination strategy (e.g., distributed optimization, reinforcement learning)
- Information sharing mechanisms
- Coordination constraints or rules
- Performance metrics for coordination

If multiple coordination approaches are described, list all. If coordination is not clearly explained, write "Coordination mechanism not specified".

- **Scalability and Resilience Characteristics**:

  Extract information about the protocol's scalability and resilience:

- Maximum number of agents tested
- Performance under different scale conditions
- Resilience to communication failures
- Adaptability to changing system conditions

Look in results, discussion, or limitations sections. If scalability is not directly addressed, note "Scalability not explicitly evaluated".

- **Energy System Context**:

  Describe the specific energy system context:

- Type of energy system (smart grid, residential energy, distribution network)
- Specific energy resources involved (distributed energy storage, electric vehicles, flexible loads)
- Operational modes (grid-connected, islanded)

Provide as much detail as possible from the methods and context sections. If system context is unclear, write "System context not fully specified".

- **Performance Outcomes**:

  Identify key performance outcomes of the agent communication protocol:

- Quantitative performance metrics (cost reductions, efficiency improvements)
- System-level benefits (reduced congestion, emissions, energy losses)
- Individual agent/prosumer level benefits

Extract numerical values if provided. If no clear outcomes are specified, note "Performance outcomes not quantified".

Results

Characteristics of Included Studies

Study	Study Focus	Protocol Type	Implementation Scale	Maintenance Context
Mohammed, 2017	Cyber-physical systems, communication/control for operational security	Data-centric middleware, protocol translation, scalable multi-agent system	Conceptual, hardware prototype	Grid/microgrid protection, electric vehicle integration, adaptive protection
Asgeirsson et al., 2007	Aggregation/market integration of distributed energy resources	Inter-Control Center Communications Protocol (ICCP), Secure Sockets Layer/Virtual Private Network (SSL/VPN), Extensible Markup Language (XML) Web Services	Field demonstration, more than 20 distributed energy resources	Distributed energy resource aggregation, economic dispatch, market participation

Study	Study Focus	Protocol Type	Implementation Scale	Maintenance Context
Chouhan, 2017	Multi-agent system for distribution automation with distributed generation/microgrids	Foundation for Intelligent Physical Agents (FIPA), decentralized peer-to-peer	Simulation, real-world test system	Fault location, isolation, restoration (FLIR)
Abdelhamid et al., 2022	Decentralized multi-agent system for self-healing	Decentralized multi-agent system (Java Agent DEvelopment Framework, JADE)	Simulation, 22 kV radial system	Fault detection, isolation, service restoration
Jane et al., 2020	Adaptive leader election for tactical microgrids	Decentralized, distributed, multi-hop	Simulation	Leader election, optimal power flow, grid stability
Zhang, No date found	Multi-agent optimization/learning for smart/resilient grids	Distributed, neighbor communication, reinforcement learning	Conceptual, simulation	Volt/var control, power management, resilience
Wei, 2019	Multi-agent system-based coordination of microgrids	Decentralized, consensus, hybrid	Simulation, multiple microgrids	Coordination, economic dispatch, reliability
Sharma et al., 2017	Distributed control for energy storage under cyber-attack	Distributed, leader-follower, consensus	Simulation, medium-voltage system	Peak shaving, cyber-attack resilience
Nguyen and Flueck, 2012	Agent-based restoration with energy storage	Distributed, autonomous agents	Simulation, IEEE 34-node feeder	Fault detection, restoration, islanding
Nazari et al., 2020	Resilient distributed frequency control	Distributed, neighbor/multi-hop	Simulation, large-scale grids	Frequency regulation, communication failure resilience
Charbonnier et al., 2023	Deep multi-agent reinforcement learning for residential flexibility	Centralized factored critic, minimal data sharing	Simulation, more than 30 homes	Residential flexibility, electric vehicle/heating coordination
Peskar et al., 2024	Adaptive agent-based control for naval microgrids	Decentralized, direct neighbor	Simulation, 3 batteries plus generator	Battery management, adaptive strategy

Study	Study Focus	Protocol Type	Implementation Scale	Maintenance Context
Sharma et al., 2024	Distributed application architecture/API for grid operations	Distributed layered, Common Information Model (CIM)-based API	Conceptual, reference implementation	Modular grid operations, distributed energy resource management system/advanced distribution management system integration
Das et al., 2024	Adaptive dynamic programming for distributed energy resource coordination	Reinforcement learning (adaptive dynamic programming, deterministic policy gradient), actor-critic	Simulation, IEEE 123-node	Distributed energy resource dispatch, battery energy storage system life optimization
Moheuddin et al., 2009	Scalable, reconfigurable distributed multi-agent system	Decentralized, FIPA/JADE, clustering	Simulation, large power system	Fault identification, reconfiguration
García et al., 2010	Agent-based distributed smart-grid management	Distributed, event-driven, middleware	Field-tested, large deployments	Network management, device configuration, monitoring
Charbonnier et al., 2022	Scalable multi-agent reinforcement learning for residential energy	Decentralized, Q-learning, fixed Q-tables	Simulation	Residential flexibility, electric vehicle/heating/loads
Schmutzler et al., 2011	Web services for distributed energy resources in IEC 61850	Distributed, Devices Profile for Web Services (DPWS), Web Services (WS-*)	Proof-of-concept, electric vehicle use case	Distributed energy resource integration, plug-and-play, asset management
Sun and Ye, 2011	Scalable multi-agent system communications for islanded microgrids	Distributed, token-ring, multi-hop	Simulation	Microgrid communications, failure detection

Study	Study Focus	Protocol Type	Implementation Scale	Maintenance Context
Sampaio et al., 2020	Multi-agent system-based self-healing/adaptive protection	Distributed, negotiation	Test bench, digital relays	Self-healing, adaptive protection, distributed generation
Yang et al., 2021	Multi-agent system-based optimal load restoration	Distributed, peer-to-peer, consensus	Simulation	Critical load restoration, distributed energy resources
Al-Hinai and Alhelou, 2021	Multi-agent system for restoration in smart grids	Decentralized (JADE), binary integer linear programming	Simulation, 14/70-bus	Fault location, isolation, restoration
Ding et al., 2022	Federated architecture for distributed energy resource management systems	Distributed/federated, hierarchical	Conceptual, system-level specifications	Distributed energy resource aggregation, economic dispatch, transmission and distribution services
Bhattacharya et al., 2019	Incentive-based distributed energy resource coordination	Hierarchical, ZeroMQ (ZMQ) publish/subscribe, VPN	Simulation, more than 10,000 devices	Frequency response, regulation, ramping
Mihailescu et al., 2011	Dynamic coalition for virtual power stations	Distributed, coalition formation	Conceptual, algorithmic	Virtual power station creation, adaptation, stability

Across 25 studies of multi-agent system protocols for grid and distributed energy resource management, the following patterns were observed:

- Protocol Type:
  - Distributed multi-agent system approaches were most common (13 studies).
  - Decentralized multi-agent system protocols were used in 8 studies.
  - Middleware, web services, or API-based protocols (including FIPA, JADE, ICCP, DPWS, CIM, and others) were found in 10 studies.
  - Centralized or hierarchical architectures were used in 3 studies.
  - Reinforcement learning or other optimization-based protocols were found in 4 studies.
  - Hybrid or other approaches (such as consensus or coalition formation) were found in 4 studies.
- Implementation Scale:
  - 16 studies used simulation only.

  - 2 studies combined simulation with real-world test systems or hardware prototypes.
  - 5 studies were field-tested, bench-tested, or included a reference implementation.
  - 2 studies were conceptual or algorithmic only.

- Maintenance Context (Application Domain):

  - Fault detection, restoration, self-healing, or adaptive protection was addressed in 8 studies.
  - Distributed energy resource or market aggregation, dispatch, or coordination was addressed in 8 studies.
  - Grid or microgrid stability, operation, or optimization was addressed in 6 studies.
  - Residential flexibility, electric vehicle, heating, or load management was addressed in 2 studies.
  - Battery or energy storage management was addressed in 3 studies.
  - Communication, cybersecurity, or resilience was addressed in 2 studies.
  - Network or device management or asset management was addressed in 2 studies.

We did not find mention of implementation scale information for studies outside these categories, and some studies addressed multiple protocol types or application domains.

Thematic Analysis

Protocol Adaptation Mechanisms

Study	Protocol Type	Adaptation Method	Security Features	Scalability Approach
Mohammed, 2017	Data-centric middleware, protocol translation	Adaptive protection, protocol gateway	Cybersecurity testbeds, resilience to attacks	Scalable cloud-based multi-agent system, multi-lingual system
Asgeirsson et al., 2007	ICCP, SSL/VPN, XML Web Services	Standard protocol integration, market procedures	SSL, VPN, secure communications	Standards-based technology, aggregation, process historian
Chouhan, 2017	FIPA, decentralized peer-to-peer	Q-learning, hybrid control	No mention found	Hierarchical multi-agent system, reduced communication overhead
Abdelhamid et al., 2022	Decentralized multi-agent system (JADE)	Expert rules, agent specialization	No mention found	Fully decentralized, agent types (zone, feeder, microgrid)
Jane et al., 2020	Decentralized, distributed, multi-hop	Adaptive leader election, desirability index	No mention found	Communication complexity reduction (2N)

Study	Protocol Type	Adaptation Method	Security Features	Scalability Approach
Zhang, No date found	Distributed, neighbor communications, reinforcement learning	Model-free reinforcement learning, bi-level, consensus	Privacy-preserving, safe reinforcement learning	Distributed optimization, local data only
Wei, 2019	Decentralized, consensus, hybrid	Evolutionary/genetic algorithms, consensus	No mention found	Coordination area selection, scalable multi-agent system
Sharma et al., 2017	Distributed, leader-follower, consensus	Fuzzy logic deviation detection	Cyber-attack resilience	Arbitrary topology, consensus-based control
Nguyen and Flueck, 2012	Distributed, autonomous agents	Local view, autonomy	No mention found	Fully distributed, scalable
Nazari et al., 2020	Distributed, neighbor/multi-hop	Dynamic communication hops, resilient distributed frequency regulation	Resilience to communication failures	Scalable to large grids, local communications
Charbonnier et al., 2023	Centralized factored critic, minimal data	Deep reinforcement learning, factored critic	Privacy (no data sharing)	Minimal communications, scalable reinforcement learning
Peskar et al., 2024	Decentralized, direct neighbor	Adaptive strategy mapping	No mention found	Priority-based run order, small-scale
Sharma et al., 2024	Distributed layered, CIM-based API	Laminar coordination, modular applications	Securability, standards-based	Layered, extensible, scalable APIs
Das et al., 2024	Reinforcement learning (adaptive dynamic programming, deterministic policy gradient), actor-critic	Off-policy deterministic policy gradient, policy-based exploration	No mention found	IEEE 123-node, scalable reinforcement learning
Moheuddin et al., 2009	Decentralized, FIPA/JADE, clustering	Spectral clustering, cost function	No mention found	Cluster agents, reduced communication overhead
García et al., 2010	Distributed, event-driven, middleware	Rule-engines, data ontologies	Secure measurement retrieval	Event-bus, agent specialization

Study	Protocol Type	Adaptation Method	Security Features	Scalability Approach
Charbonnier et al., 2022	Decentralized, Q-learning, fixed Q-tables	Off-line convex optimization, reward isolation	No data sharing	Fixed Q-tables, scalable reinforcement learning
Schmutzler et al., 2011	Distributed, DPWS, WS-*	Plug-and-play, protocol mapping	WS-* compliance	Dynamic distributed energy resource discovery, scalable
Sun and Ye, 2011	Distributed, token-ring, multi-hop	Token-ring, failure detection	Failure detection	Parallelized message propagation
Sampaio et al., 2020	Distributed, negotiation	Negotiation, adaptive protection	No mention found	Multi-agent system, negotiation, adaptive settings
Yang et al., 2021	Distributed, peer-to-peer, consensus	Min/max-consensus, bias min-consensus	No mention found	Peer-to-peer, adaptive to topology
Al-Hinai and Alhelou, 2021	Decentralized (JADE), binary integer linear programming	Pre-calculation, binary integer linear programming	No mention found	Decentralized, scalable to 70-bus
Ding et al., 2022	Distributed/federated, hierarchical	Federated resource scheduling, constrained dispatch	Secure, federated	Substation-level aggregation
Bhattacharya et al., 2019	Hierarchical, ZMQ publish/subscribe, VPN	Multi-objective optimization, aggregator hierarchy	VPN, Transport Layer Security (TLS) encryption	More than 10,000 devices, co-simulation
Mihailescu et al., 2011	Distributed, coalition formation	Dynamic coalition, negotiation	No mention found	Open-ended adaptation, coalitional games

Protocol Type:

- Distributed protocol types were the most common, found in 13 studies.
- Decentralized approaches were used in 8 studies.
- Reinforcement learning-based protocols were found in 4 studies.
- Hierarchical, peer-to-peer, and multi-hop protocols were each found in 2–3 studies.
- Middleware, federated, layered, FIPA, JADE, clustering, event-driven, centralized, hybrid, ZMQ, DPWS/WS-*, token-ring, binary integer linear programming, and coalition formation were each found in 1–3 studies.

- We found protocol type information for all studies.

Adaptation Method:

- Reinforcement learning-based adaptation (including Q-learning, deep reinforcement learning, model-free reinforcement learning, actor-critic, off-policy) was used in 4 studies.
- Consensus-based adaptation (including min/max-consensus, leader election) was found in 3 studies.
- Negotiation and rule-based/expert rules were each found in 2 studies.
- Other adaptation methods (clustering, evolutionary/genetic, fuzzy logic, protocol mapping/integration, adaptive protection/strategy, modular/laminar, multi-objective optimization, coalition, pre-calculation/binary integer linear programming, plug-and-play, failure detection, market procedures, data ontologies, cost function, aggregator hierarchy, dynamic communications, reward isolation, convex optimization, factored critic, local view/autonomy, federated resource scheduling, constrained dispatch) were each found in 1 study.
- We found adaptation method information for all studies.

Security Features:

- Security features were specified in 13 studies.
  - Of these, resilience to attacks or communication failures was mentioned in 3 studies.
  - Privacy or no data sharing was mentioned in 3 studies.
  - Encryption (SSL, VPN, TLS) was mentioned in 2 studies.
  - Secure or federated approaches were found in 2 studies.
  - Secure measurement retrieval, WS-* compliance, securability/standards-based, and failure detection were each found in 1 study.
- We did not find mention of security features in 12 studies.

Scalability Approach:

- Distributed or decentralized scalability approaches were found in 7 studies.
- Scalable reinforcement learning approaches were found in 3 studies.
- Reduced communication overhead was found in 3 studies.
- Aggregation and local communication/data approaches were each found in 2 studies.
- Hierarchical, cloud-based, layered/extensible, large-scale (more than 10,000 devices), event-bus, priority-based, small-scale, peer-to-peer, adaptive topology/settings, fixed Q-tables, dynamic discovery, parallelized, multi-agent system, substation-level, co-simulation, open-ended/coalitional games, IEEE 123-node, and agent specialization/types were each found in 1 study.
- We found scalability approach information for all studies.

Coordination Architectures

Study	Architecture Type	Communication Model	Resource Management	Performance Metrics
Mohammed, 2017	Centralized/decentralized hybrid	Data-centric bus, protocol translation	Microgrid/electric vehicle control, adaptive protection	No mention found

Study	Architecture Type	Communication Model	Resource Management	Performance Metrics
Asgeirsson et al., 2007	Centralized with distributed elements	ICCP, web services	Distributed energy resource aggregation, economic dispatch	Market participation, operational control
Chouhan, 2017	Hybrid (centralized/decentralized)	FIPA, peer-to-peer	Fault location, isolation, restoration, switch optimization	Agent communications, restoration speed
Abdelhamid et al., 2022	Decentralized multi-agent system	JADE, agent communications	Self-healing, distributed generation management	No mention found
Jane et al., 2020	Decentralized	Distributed, multi-hop	Leader election, power flow	Communication complexity (2N)
Zhang, No date found	Distributed, hierarchical	Neighbor communications, leader-follower	Volt/var, power management, resilience	No mention found
Wei, 2019	Decentralized/hybrid	Consensus, market	Microgrid coordination, economic dispatch	Reliability, scalability
Sharma et al., 2017	Distributed	Leader-follower, consensus	Distributed energy storage system peak shaving	No mention found
Nguyen and Flueck, 2012	Distributed	Local agent communications	Restoration, islanding	No mention found
Nazari et al., 2020	Distributed	Neighbor/multi-hop	Frequency regulation	Stability, fair power sharing
Charbonnier et al., 2023	Centralized critic, distributed agents	Minimal communications	Residential flexibility	Training time, user savings
Peskar et al., 2024	Decentralized	Direct neighbor	Battery/generator management	Battery/generator remaining useful life, temperature
Sharma et al., 2024	Distributed layered	CIM-based API	Modular grid operations	No mention found
Das et al., 2024	Distributed reinforcement learning	Actor-critic	Distributed energy resource/battery energy storage system dispatch	Optimization gap, cost savings
Moheuddin et al., 2009	Decentralized, clustered	FIPA/JADE, cluster communications	Fault reconfiguration	Communication overhead, decision time
García et al., 2010	Distributed	Event-bus, rule-engines	Network management, configuration	No mention found

Study	Architecture Type	Communication Model	Resource Management	Performance Metrics
Charbonnier et al., 2022	Decentralized	Q-learning, fixed Q-tables	Residential flexibility	Cost, congestion, emissions
Schmutzler et al., 2011	Distributed	DPWS, WS-*	Distributed energy resource plug-and-play	Latency, scalability (qualitative)
Sun and Ye, 2011	Distributed	Token-ring, multi-hop	Microgrid communications	No mention found
Sampaio et al., 2020	Distributed	Negotiation	Self-healing, adaptive protection	No mention found
Yang et al., 2021	Distributed	Peer-to-peer, consensus	Load restoration	No mention found
Al-Hinai and Alhelou, 2021	Decentralized	JADE, binary integer linear programming	Restoration	Computational efficiency
Ding et al., 2022	Distributed/federated	Hierarchical, federated resource scheduling	Distributed energy resource aggregation, dispatch	No mention found
Bhattacharya et al., 2019	Hierarchical	ZMQ publish/subscribe, VPN	Frequency, regulation, ramping	Response time, reserve targets
Mihailescu et al., 2011	Distributed	Coalition formation	Virtual power station creation, adaptation	Stability (qualitative)

Architecture Type:

- Distributed architectures were found in 13 studies.
- Decentralized architectures were found in 7 studies.
- Hybrid, hierarchical, layered, federated, or clustered architectures were found in 10 studies.
- Many studies described more than one architecture type (such as hybrid or layered).

Communication Model:

- Peer-to-peer, neighbor, or local agent communication was found in 7 studies.
- Consensus, leader-follower, negotiation, or coalition-based communication was found in 8 studies.
- Bus, event-bus, or protocol translation models were found in 2 studies.
- Web services, APIs, publish-subscribe, or token-ring models were found in 5 studies.
- JADE, FIPA, or agent-based communication frameworks were found in 4 studies.
- Market-based communication was found in 1 study.
- Minimal communication was found in 1 study.
- We found 2 studies using other models such as Q-learning or actor-critic.

Resource Management Approaches:

- Distributed energy resource management, aggregation, dispatch, or plug-and-play was found in 5 studies.
- Microgrid, islanding, restoration, or self-healing was found in 5 studies.
- Flexibility management (residential or load) was found in 2 studies.
- Battery or generator management was found in 1 study.
- Frequency or voltage regulation was found in 2 studies.
- Peak shaving, economic dispatch, or market participation was found in 2 studies.
- Fault reconfiguration was found in 1 study.
- Other resource management approaches (such as network management, leader election, modular operations, etc.) were found in 7 studies.

Performance Metrics:

- We found quantified performance metrics in 14 studies (including measures such as cost, latency, response time, scalability, user savings, and others).
- We did not find mention of quantified performance metrics in 11 studies.

Security and Scalability Integration

- Security and scalability are often addressed together in protocol adaptation, with a focus on:
  - Resilience to cyber-attacks and communication failures (e.g., through protocol-level security such as Secure Sockets Layer, Virtual Private Network, Web Services compliance).
  - Middleware for secure data exchange.
  - Design choices that minimize communication, such as fixed Q-tables or local-only data.
- Scalability is achieved through:
  - Clustering.
  - Hierarchical control.
  - Distributed optimization.
  - Minimal data sharing.
- Empirical validation is limited :
  - Explicit evaluation of security outcomes is rare.
  - Quantitative scalability metrics are inconsistently reported.
- Included studies support the feasibility of secure, scalable agent communication, but the available evidence base is limited in empirical validation.

Maintenance-Specific Implementations

- Maintenance contexts addressed in the included studies:
  - Fault detection, isolation, restoration, self-healing, and adaptive protection.
  - Economic dispatch and resource allocation.
- Protocol adaptation for maintenance :
  - Rapid restoration is supported by agent-based protocols (e.g., Chouhan, Yang, Al-Hinai).
  - Resilience to faults and cyber-attacks is a focus in several studies (e.g., Sharma et al., Nazari, Mohammed).

  - Efficient resource allocation is addressed in studies on aggregation and dispatch (e.g., Asgeirsson, Bhattacharya, Das).
- Agent-based approaches enable :
  - Local autonomy.
  - Rapid response.
  - Adaptability to changing system conditions.
- Comparability and evaluation :
  - The diversity of maintenance tasks and system contexts in the included studies complicates direct comparison.
  - Few studies provide comprehensive, quantitative evaluation of maintenance outcomes.

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