

Agent Identity URI Scheme: Topology-Independent Naming and Capability-Based Discovery for Multi-Agent Systems

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Abstract. Multi-agent systems face a fundamental architectural flaw: agent identity is bound to network location. When agents migrate between providers, scale across instances, or federate across organizations, URI-based identity schemes break references, fragment audit trails, and require centralized coordination. We propose the `agent://` URI scheme, which decouples identity from topology through three orthogonal components: a trust root establishing organizational authority, a hierarchical capability path enabling semantic discovery, and a sortable unique identifier providing stable reference.

The scheme enables capability-based discovery through DHT key derivation, where queries return agents by what they do rather than where they are. Trust-root scoping prevents cross-organization pollution while permitting federation when desired. Cryptographic attestation via PASETO tokens binds capability claims to agent identity, enabling verification without real-time contact with the issuing authority.

We evaluate the scheme across four dimensions. On capability expressiveness, the grammar achieves 100% coverage on 369 production tools from five agent frameworks with zero namespace collision. On discovery precision, trust-scoped prefix matching achieves perfect F1=1.0 across 10,000 agents with result sets averaging 128 agents for prefix queries and 39 for exact queries. On identity stability, we prove that migration preserves identity and resolution completes in $O(\log N)$ hops. On performance, all operations complete in under 5 microseconds, orders of magnitude below network latency. The `agent://` URI scheme provides a formally-specified, practically-evaluated foundation for decentralized agent identity and capability-based discovery.

Keywords: multi-agent systems, agent identity, decentralized discovery, capability-based routing, URI schemes

1 Introduction

Consider an invoice-approval agent deployed at <https://agents.acme.com/approver>. The company migrates cloud providers. The URI changes. Every workflow referencing that URI breaks. The agent’s *identity* was its *location*.

Now consider a harder problem. A procurement agent needs to find any agent capable of “hazmat shipping quotes” across organizational boundaries. The requester knows what capability it needs but not which provider offers it or where their agents run. Current agent systems provide no mechanism for this query.

These scenarios share a root cause. Like the early internet before DNS separated names

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from addresses, agent systems today conflate identity with location. Saltzer identified this architectural error in 1982 [Saltzer(1982)]: names should be resolved to addresses, not used as addresses directly. Thirty years of multi-agent systems research has not addressed this fundamental issue.

The FIPA Directory Facilitator assumes a single platform with centralized registration [FIPA(2004)]. The A2A protocol binds agent identity to Agent Card URIs [Linux Foundation(2025)]. Decentralized Identifiers provide generic identity primitives but lack capability semantics for agent discovery [Sporny et al.(2022)]. Each approach either centralizes control, couples identity to topology, or ignores the capability-based discovery that agents require.

We propose the `agent://` URI scheme, designed from first principles to separate concerns:

Topology-independent identity. A URI like `agent://acme.com/workflow/approval/agent_01h...` identifies an agent regardless of which server, cloud provider, or geographic region hosts it. Migration updates a DHT record; the URI remains stable.

Capability-based discovery. The capability path `/workflow/approval` enables queries like “find agents that can approve workflows.” DHT key derivation from capability paths provides $O(\log N)$ lookup without centralized registries.

Trust-root federation. The authority component `acme.com` identifies the organization vouching for the agent. Cross-organization discovery is explicit: query across trust roots or within one. No implicit trust transitivity.

Cryptographic attestation. PASETO tokens issued by trust roots bind agent identity to capability claims. Verification requires only the trust root’s public key, cached after initial fetch.

Our evaluation demonstrates that these properties hold in practice:

1. **Expressiveness.** The capability path grammar represents 100% of 369 production tools from LangChain, CrewAI, MCP, AutoGen, and smolagents with zero namespace collision.
2. **Discovery precision.** Trust-scoped prefix matching achieves $F1=1.0$ across 10,000 agents with result sets averaging 128 agents for broad queries and 39 for targeted queries.
3. **Identity stability.** We prove formally that migration preserves identity and resolution completes in $O(\log N)$ hops regardless of migration history.
4. **Performance.** URI parsing, canonicalization, and prefix matching complete in under 5 microseconds, negligible compared to network latency.

The contribution is not incremental improvement but architectural correction. Like DNS for network addresses, the `agent://` URI scheme separates the naming problem from the routing problem, enabling stable identity, semantic discovery, and federated trust without centralized control.

2 Background and Problem Statement

This section establishes the technical context and derives requirements from concrete failure modes of current approaches.

2.1 Agent Identity in Multi-Agent Systems

The Foundation for Intelligent Physical Agents (FIPA) specification, developed in the late 1990s, remains the most complete formalization of agent infrastructure [FIPA(2002), FIPA(2004)]. FIPA defines two directory services: the Agent Management System (AMS) tracks agent lifecycle within a platform, and the Directory Facilitator (DF) registers agent

capabilities for discovery.

The FIPA model assumes a contained environment. Agents register with the DF on their platform; queries go to that DF; results return agents from that platform. Cross-platform federation requires federated DFs exchanging registration information—a coordination problem that scales poorly as platform count increases [Denegri and Simari(2007)].

The model’s deeper limitation is identity binding. A FIPA agent’s identity is its **agent-identifier**, which includes the agent-name and a set of addresses. When addresses change, the identity changes. Migration requires re-registration. Audit logs referencing old identities become ambiguous: was it the same agent or a different one?

Modern agent systems inherit this conflation. The A2A protocol identifies agents by their Agent Card URI [Linux Foundation(2025)]. LangChain tools are identified by their Python module path [LangChain Inc.(2023)]. MCP servers are identified by their transport endpoint [Anthropic(2024)]. In each case, the identifier contains location information. Change the location, break the identity.

2.2 The Name/Address Distinction

Saltzer’s 1982 analysis of network naming distinguishes three concepts [Saltzer(1982)]: *names* identify entities, *addresses* locate entities, and *routes* specify how to reach entities. The paper argues that conflating these concepts creates brittleness: changes to routing or location force changes to identification.

The postal system illustrates this principle. Your name remains stable even as you move between apartments, cities, or countries. The postal service maintains a forwarding database that maps your name to your current address. Letters addressed to “Jane Smith” reach you regardless of whether you live in Boston or Berlin. Agent systems need this same separation: a stable name that survives changes in where the agent actually runs.

Applied to agents, the distinction suggests:

- **Name:** A stable identifier for the logical agent (independent of deployment)
- **Address:** The current network endpoint(s) where the agent can be contacted
- **Route:** The protocol and path to reach that endpoint

Current agent systems use URIS as names. But URIS contain addressing information (host, port). They specify routing (scheme implies protocol). They conflate all three concepts into a single string.

The `agent://` URI scheme applies Saltzer’s analysis. The URI is a name. Resolution maps the name to addresses. Routing protocols (HTTPS, gRPC, WebSocket) are negotiated after resolution. The name survives changes to address and route.

2.3 Requirements for Agent Identity

From the failure modes of current approaches, we derive five requirements:

R1: Topology Independence. Agent identity must not change when the agent migrates between hosts, cloud providers, or geographic regions. Audit logs and cached references must remain valid.

R2: Capability Semantics. The identity scheme must support discovery by capability. “Find agents that can approve invoices” should be a supported query, not just “find the agent at this URI.”

R3: Decentralized Resolution. No single registry should be required for resolution. The scheme must function in federated environments where organizations do not share infrastructure.

R4: Organizational Scoping. Queries should be scorable to trust boundaries. An

organization should be able to discover only its own agents, or explicitly opt into cross-organization discovery.

R5: Verifiable Claims. Capability claims must be cryptographically verifiable. An agent claiming “financial transaction authority up to \$10,000” must present proof signed by an authority the verifier trusts.

3 The Agent URI Scheme

This section specifies the `agent://` URI syntax, defines component semantics, and establishes normalization rules for equivalence testing.

3.1 URI Structure

An agent URI follows RFC 3986 generic syntax [Berners-Lee et al.(2005)] with agent-specific constraints:

```
agent://trust-root/capability-path/agent-id[?query][#fragment]
```

Example:

```
agent://anthropic.com/assistant/chat/agent_01h455vb4pex5vsknk084sn02q
```

The scheme `agent` signals that this URI identifies an agent and should be resolved through the agent discovery protocol (Section 4).

3.2 Component Semantics

Trust Root. The authority component identifies the organization vouching for the agent. It follows DNS hostname syntax and publishes verification keys at a well-known endpoint. The trust root is analogous to a passport-issuing authority: it attests to the agent’s identity and capabilities within its jurisdiction. Just as a passport from France is valid worldwide but issued only by France, an agent’s attestation from `acme.com` is verifiable by anyone but issued only by Acme.

Capability Path. The path component describes what the agent does using hierarchical segments. Each segment is a lowercase alphanumeric string with hyphens permitted. The path `/workflow/approval/invoice` indicates specialization: workflow capabilities, specifically approval, specifically for invoices.

Capability paths support prefix matching. A query for `/workflow/approval` returns agents at that path and all child paths (`/workflow/approval/invoice`, `/workflow/approval/expense`). This enables discovery at varying granularity—like asking “find me any specialist in cardiology” rather than “find me Dr. Smith at Boston General.”

Agent Identifier. The final path segment is a TypeID [Jetify(2023)]: a type prefix (`agent_`) followed by a base32-encoded UUIDv7 [Peabody and Davis(2024)]. TypeIDs are globally unique, lexicographically sortable by creation time, and URI-safe. The type prefix provides runtime type checking; the UUIDv7 suffix ensures uniqueness without coordination.

Query String. Optional parameters for version negotiation, feature flags, or other metadata. Not part of identity—two URIs differing only in query string may reference the same agent with different interaction parameters.

Fragment. Optional sub-agent reference. Reserved for future use in composite agent scenarios.

3.3 Normalization and Equivalence

Two URIs denote the same agent if and only if their canonical forms are byte-equal. Canonicalization applies:

1. **Scheme:** Lowercase (`agent`, not `AGENT`)
2. **Trust root:** Lowercase, no trailing dot
3. **Capability path:** Lowercase, no trailing slash, percent-decoding of unreserved characters
4. **Agent ID:** Lowercase (base32 is case-insensitive)
5. **Query and fragment:** Stripped (not part of identity)

The canonical form is used for DHT key derivation. Different surface representations resolve to the same agent if their canonical forms match.

3.4 Formal Specification

The URI syntax in ABNF (RFC 5234):

```

agent-uri      = "agent://" trust-root "/" capability-path
                  "/" agent-id [ "?" query ] [ "#" fragment ]

trust-root     = hostname
hostname       = label *( "." label )
label          = ALPHA *( ALPHA / DIGIT / "-" )

capability-path = segment *( "/" segment )
segment        = 1*( ALPHA / DIGIT / "-" )

agent-id       = type-prefix suffix
type-prefix    = "agent_"
suffix         = 26base32char
base32char     = ALPHA / "2" / "3" / "4" / "5" / "6" / "7"
                  ; Base32 alphabet excluding I, L, O, U (case-insensitive)

query          = *( pchar / "/" / "?" )
fragment       = *( pchar / "/" / "?" )
pchar          = unreserved / pct-encoded / sub-delims / ":" / "@"
unreserved    = ALPHA / DIGIT / "-" / "." / "_" / "~"
pct-encoded   = "%" HEXDIG HEXDIG
sub-delims    = !"!" / $"$" / "&" / ',' / "(" / ")"
                  / "*" / "+" / "," / ";" / "="

```

The grammar enforces structural validity. Semantic validity (trust root exists, capability path is meaningful) is checked at registration and verification time.

4 Discovery and Resolution

This section defines how agents register capabilities and how requesters discover agents, using a Kademlia-style DHT with trust-root scoping.

4.1 DHT Key Derivation

The DHT key for a capability path is derived by hashing the trust root and path together:

$$\text{key} = \text{SHA256}(\text{canonical}(\text{trust_root}) \parallel \text{canonical}(\text{cap_path})) \quad (1)$$

This derivation has two critical properties:

Trust-root scoping. The trust root is part of the hash input. A query for `acme.com/workflow/approval` and `globex.com/workflow/approval` produces different

keys, preventing cross-organization pollution. This is deliberate: organizations can see only what they explicitly query for, maintaining trust boundaries by default.

Deterministic lookup. Given a trust root and capability path, any node can compute the key and query the DHT directly. No metadata lookup is required.

For prefix queries, keys are derived at each level of the capability path. A query for `/workflow/approval` with prefix matching queries keys for `/workflow/approval`, `/workflow/approval/*`, and so on, collecting results across the subtree.

4.2 Registration Protocol

An agent registers by storing a registration record at the DHT key for its capability path:

```
Registration {
    agent_uri: AgentUri,
    endpoints: Vec<Endpoint>,
    attestation: Option<String>, // PASETO token
    expires_at: Timestamp,
    registered_at: Timestamp,
}
```

The agent registers at its most specific capability level. An agent that only handles invoice approvals registers at `/workflow/approval/invoice`, not `/workflow/approval`. This precision improves discovery accuracy.

Registration requires presenting a valid attestation token (Section 5). The DHT nodes verify the attestation before storing the record, preventing registration of unattested capability claims.

4.3 Lookup Protocol

Discovery proceeds in three steps:

1. **Key derivation.** Compute DHT key from trust root and capability path.
2. **DHT lookup.** Query Kademia [Maymounkov and Mazières(2002)] for records at that key (exact match) or keys in the subtree (prefix match).
3. **Result filtering.** Optionally verify attestations on returned records; filter by query parameters.

Prefix matching returns agents registered at the queried path and all descendant paths. A query for `/workflow` returns agents at `/workflow`, `/workflow/approval`, `/workflow/approval/invoice`, and so on.

For cross-trust-root discovery, the requester queries each trust root separately and merges results. No global key derivation exists—trust boundaries are explicit.

4.4 Resolution Guarantees

Resolution inherits Kademia's properties:

Theorem 1 (Bounded Resolution). Resolution of any agent URI terminates in $O(\log N)$ DHT hops, where N is the number of DHT nodes.

Proof. DHT key derivation produces a 256-bit hash. Kademia lookup proceeds by iteratively querying nodes closer to the target key in XOR distance. Each iteration at least halves the distance to the target. After $O(\log N)$ iterations, we reach nodes responsible for the key, which return registered endpoints. \square

Corollary 1. Resolution cost is independent of migration history. An agent that has migrated 100 times has the same resolution cost as one that never migrated.

Theorem 2 (Eventual Consistency). After migration with DHT record update, all subsequent lookups return the new endpoint within time T_{prop} , where $T_{\text{prop}} \leq k \cdot \text{RTT}_{\max}$.

Proof sketch. The agent updates its DHT record via PUT. Kademlia replicates to k closest nodes. After propagation completes (bounded by k round trips), all replicas hold the updated endpoint. Subsequent lookups query these replicas. \square

5 Security and Trust

This section defines the trust model, attestation format, and verification protocol.

5.1 Trust Root Model

A trust root is an organization that vouches for agents' existence and capabilities. The trust root:

1. Operates agent infrastructure (or delegates operation)
2. Issues attestation tokens binding agents to capabilities
3. Publishes verification keys at a well-known endpoint

Key publication follows a standard format:

```
GET https://{{trust-root}}/.well-known/agent-keys.json

{
  "trust_root": "acme.com",
  "keys": [
    {
      "kid": "key-2026-01",
      "algorithm": "Ed25519",
      "public_key": "<base64>",
      "not_before": "2026-01-01T00:00:00Z",
      "not_after": "2027-01-01T00:00:00Z"
    }
  ]
}
```

Key rotation is supported via multiple keys with validity periods. Verifiers cache keys and refresh on verification failure.

5.2 PASETO Attestation

Attestation tokens use PASETO v4.public (Ed25519 signatures) [Arciszewski(2018)]. The payload contains:

Claim	Type	Description
iss	string	Issuing trust root
sub	string	Agent URI attested
aud	string?	Audience restriction
iat	datetime	Issued-at time
exp	datetime	Expiration time
capabilities	string[]	Claimable paths

Table 1: PASETO attestation claims

The optional `aud` claim restricts attestation validity to specific verifiers. For example, `aud: "api.globex.com"` limits the attestation to interactions with Globex's API, preventing replay to other parties. This enables issuing narrowly-scoped attestations for specific business relationships without granting broad authority.

When to use `aud`. Audience restriction is appropriate for high-value transactions (financial approvals, contract signing), sensitive data access (personal information, trade secrets),

and compliance-driven interactions where audit trails must demonstrate specific authorization. Conversely, general-purpose agents handling public services, discovery responses, or low-risk operations should omit `aud` to maximize interoperability.

Multiple parties. When an agent interacts with multiple specific parties, it can hold multiple attestations with different `aud` values—one per relationship. Alternatively, agents with broad interaction patterns should use a general attestation (no `aud`) for routine operations and request audience-restricted attestations only for sensitive interactions.

Verification behavior. If `aud` is present in the attestation, the verifier *must* match: a verifier not named in `aud` rejects the attestation. If `aud` is absent, any verifier accepts the attestation (subject to other claim checks). This asymmetry ensures that audience restriction is opt-in per attestation while remaining invisible to general-purpose verification flows.

The `capabilities` claim constrains which capability paths the agent may register at. An attestation with `capabilities: ["workflow/approval"]` authorizes registration at `/workflow/approval` and any child path, but not `/workflow/review` or `/financial`.

5.3 Capability Binding

Verification checks that the agent's URI capability path is covered by at least one entry in the attestation's `capabilities` claim:

$$\text{covered}(\text{path}, \text{caps}) := \exists c \in \text{caps} : \text{path.starts_with}(c) \quad (2)$$

An attestation with `capabilities: ["workflow"]` covers:

- `/workflow` (exact match)
- `/workflow/approval` (prefix match)
- `/workflow/approval/invoice` (prefix match)

But not:

- `/financial` (no prefix relationship)
- `/work` (partial string match insufficient)

5.4 Trust Federation

Cross-trust-root interaction requires explicit trust decisions:

Direct trust. The verifier maintains a list of trusted trust roots. Verification fetches keys from each and accepts attestations signed by any.

Cross-certification. Trust root A signs a statement vouching for trust root B's key. The verifier trusts A and transitively trusts B for specific scopes.

Trust anchor sets. Analogous to browser CA stores. New trust roots must be added to the set explicitly.

The specification does not mandate a federation model. Deployments choose based on their trust requirements. The URI scheme supports all models—federation is a policy decision, not a protocol constraint.

5.5 Verification Flow

Complete verification of an agent presenting URI and attestation token:

1. Parse agent URI; extract `trust_root`, `capability_path`, `agent_id`
2. Fetch/cache verification key from `trust_root`'s well-known endpoint

3. Verify PASETO signature using the key
 4. Check `exp > current time` (not expired)
 5. Check `iss == trust_root` from URI
 6. Check `sub == full agent URI`
 7. Check `capabilities` covers the URI's `capability_path`
- All checks must pass. Failure at any step rejects the attestation.

5.6 Security Considerations

This section examines threat vectors specific to the `agent://` scheme and discusses mitigations.

5.6.1 DHT Eclipse Attacks

An adversary controlling nodes surrounding a capability key could return false registration records or suppress legitimate ones. This is a general DHT concern; we inherit Kademlia's defenses.

Mitigations:

- **Multi-path verification.** Query from diverse network positions; consistent results across paths indicate authenticity.
- **Attestation verification catches fakes.** Even if the DHT returns attacker-controlled records, signature verification against the trust root's published keys rejects fraudulent attestations.
- **Kademlia's redundancy.** Records are stored on k closest nodes; eclipsing requires controlling a significant fraction of the network.

The attestation layer provides defense-in-depth: DHT manipulation can cause denial of service (hiding legitimate agents) but cannot cause acceptance of unauthorized agents.

5.6.2 Trust Root Key Compromise

A compromised trust root signing key enables issuing fraudulent attestations for arbitrary agents and capabilities under that trust root.

Mitigations:

- **Key revocation.** Trust roots publish a `revoked_keys` list at their well-known endpoint. Verifiers check this list before accepting attestations signed by any key.
- **Time-bounded attestations.** The `exp` claim limits blast radius; compromised keys can only mint attestations valid until rotation.
- **Key rotation with overlap.** Trust roots should rotate keys periodically, publishing new keys before retiring old ones. Overlapping validity windows ensure continuous operation.
- **Hardware security modules.** Production deployments should protect signing keys with HSMs, limiting exposure to compromise.

Key compromise affects only the compromised trust root's agents. Cross-trust-root isolation prevents lateral movement: compromising `acme.com`'s key grants no authority over `globex.com`'s agents.

5.6.3 Query Privacy

DHT queries reveal requester interest in specific capabilities. An adversary monitoring network traffic learns which capabilities a requester seeks, potentially enabling competitive intelligence or targeted attacks.

Trade-offs:

- **Onion routing for queries.** Route queries through multiple hops to obscure originator. Adds latency; provides strong privacy.
- **Query batching.** Include decoy queries alongside real ones. Reduces signal; increases bandwidth.
- **Local caching.** Cache discovery results aggressively. Reduces query frequency; stale results possible.

Privacy and verification exist in tension: verifying attestations requires knowing what capability is claimed, which reveals the query. This tension is noted as future work (Section 8.4). For deployments where query privacy is paramount, private information retrieval techniques may apply but are beyond this specification’s scope.

6 Evaluation

We evaluate the `agent://` URI scheme across four dimensions: capability expressiveness, discovery precision, identity stability, and performance.

6.1 Capability Expressiveness

Question: Can the capability path grammar represent real-world agent capabilities without path explosion or semantic loss?

Method: We extracted tool definitions from five production agent frameworks and applied deterministic mapping rules to generate capability paths.

Source	Description	Tools
LangChain	Gmail, Slack, SQL, files	163
CrewAI	Search, scraping, RAG	107
MCP	Filesystem, GitHub, DBs	79
AutoGen	Code execution, functions	12
smolagents	Web search, Python	8
Total		369

Table 2: Tool corpus from production agent frameworks

Results:

Metric	Threshold	Result	Status
Coverage	$\geq 90\%$	100%	Pass
Collision rate	$< 1\%$	0%	Pass
Path depth mean	[2, 4]	2.0	Pass
Path depth max	≤ 10	2	Pass

Table 3: Capability expressiveness results

The key finding: real-world tools have pre-existing categories from their source frameworks. The mapping produces paths like `filesystem/read-file`, `github/create-issue`, `slack/post-message`. Category prefixes provide natural namespace separation.

Ablation (Flat Namespace). Removing hierarchy and mapping each tool to a single segment still achieves zero collisions on this corpus, because modern frameworks use descriptive, prefixed names (`slack_post_message`, `puppeteer_navigate`). However, synthetic collision tests show that hierarchical namespaces prevent collisions that flat namespaces cannot, validating the design for future ecosystem growth.

6.2 Discovery Precision

Question: Does capability-based DHT routing return agents that can actually handle a task?

Method: We simulated a DHT with 10,000 agents distributed across 50 capability categories and issued 1,000 queries, comparing returned results to ground truth.

Metric	Threshold	Prefix	Exact
Precision	≥ 0.80	1.0	1.0
Recall	≥ 0.70	1.0	1.0
F1	≥ 0.75	1.0	1.0
Result set size	—	128.3	39.0

Table 4: Discovery precision results (N=10,000 agents, M=1,000 queries)

The key finding: trust-root scoping ensures that returned agents are always from the expected organizational domain. Every returned agent was relevant (precision 1.0), and every relevant agent was found (recall 1.0), with zero variance across all 1,000 queries.

Result set sizes scale with agent density per capability category. With 10,000 agents across 50 categories, prefix queries average 128 agents (including all descendants) while exact queries average 39 agents. The $3.3\times$ ratio reflects hierarchical accumulation: prefix queries return agents at matching and child paths. For deployments requiring smaller result sets, pagination or result limits can be applied without affecting precision.

Verification Cost at Scale. The 128-agent average for prefix queries raises a practical question: what is the verification cost for large result sets? Each attestation verification requires one Ed25519 signature check, which completes in approximately 50 microseconds on modern hardware. Verifying 128 attestations thus requires approximately 6.4 milliseconds—negligible compared to network round-trip latency (typically 10–100ms) and entirely dominated by subsequent agent interactions.

Several patterns reduce verification overhead further: *Lazy verification* verifies attestations on first contact rather than at discovery time, amortizing cost across actual interactions. *Sampling* verifies a random subset for bulk operations where statistical confidence suffices. *Caching* stores verified attestations until expiration, eliminating re-verification for repeat interactions.

For larger deployments, result sets scale linearly with agents per category. A deployment with 100,000 agents across 50 capability categories would average approximately 1,280 results for broad prefix queries. At this scale, pagination becomes essential—not for verification cost (still under 100ms for full verification) but for network transfer and client-side processing.

Ablation (Global Keys without Trust Root). Removing trust root from key derivation (`key = SHA256(capability_path)` only) causes cross-organization pollution. Queries return agents from unrelated trust roots, destroying precision. The recall “improvement” is illusory—those agents are not trusted.

Expected Degradation in Production. The evaluation uses synthetic data with perfect ground truth: registrations exactly match agent capabilities, and agents remain online throughout measurement. Real deployments will exhibit degradation from several sources:

1. **Capability drift.** Agents update capabilities without re-registering. If 10% of agents have drifted capabilities, recall drops to approximately 0.9 as some relevant agents are no longer discoverable under their registered paths.
2. **Semantic mismatch.** Query paths may not exactly match registration paths. An agent registered at `/workflow/approval/invoice` is not found by a query for

/finance/approval.

3. **Stale registrations.** Agents go offline but registrations persist until TTL expires. Discovered agents may be unreachable.

Precision remains 1.0 regardless of these factors: attestation verification filters any registration that fails cryptographic checks. Recall is the affected metric. Mitigation strategies include aggressive TTL values (hours rather than days), periodic re-registration heartbeats, and client-side retry logic for stale endpoints.

6.3 Identity Stability and Failure Modes

The URI scheme provides topology-independent identity by construction: the URI contains trust root, capability path, and agent ID—none of which include endpoint information. Migration changes only the DHT record; the URI remains stable. An agent’s identity ($u = \text{agent://T/C/I}$) survives any number of endpoint changes because T , C , and I are independent of network location.

Trust root changes are intentionally *not* transparent. If an agent changes from trust root T_1 to T_2 , its identity changes: $u_1 \neq u_2$. This is correct behavior—organizational authority changes should require re-attestation, not silent migration.

Rather than formal proofs of these properties (which hold by construction), we analyze failure modes that affect practical deployments:

Failure Mode 1: Trust Root Unavailability. If the trust root’s well-known endpoint is temporarily unavailable, verifiers cannot fetch fresh keys. *Mitigation:* Verifiers cache keys with TTL; cached keys remain valid until expiration. *Degraded operation:* New agents from that trust root cannot be verified until the endpoint recovers. *Recovery:* Automatic once the endpoint returns; no manual intervention needed.

Failure Mode 2: Attestation Expiration Mid-Session. Long-running interactions may span attestation lifetime. *Mitigation:* Agents should refresh attestations before expiration (the `exp` claim signals when renewal is needed). *Degraded operation:* Verifier rejects requests with expired attestation. *Recovery:* Agent obtains fresh attestation from trust root; interaction resumes.

Failure Mode 3: DHT Partition. Network partition isolates DHT segments; registrations become unreachable from some network locations. *Mitigation:* Kademia’s k -replication ensures multiple copies across the network. *Degraded operation:* Discovery may return incomplete results during partition. *Recovery:* Kademia self-heals when partition resolves; no data loss if $k > 1$.

Failure Mode 4: Trust Root Key Rotation. Trust root rotates signing key; old attestations remain in circulation. *Mitigation:* Well-known endpoint publishes multiple keys with validity periods (`not_before/not_after`). *Degraded operation:* None if validity windows overlap. *Best practice:* Rotate keys with overlap period; re-issue attestations before old key expires.

Compound Failure Modes. Individual failures are straightforward to diagnose; compound failures require more careful analysis.

Key Rotation + DHT Partition. A trust root rotates its signing key while the network is partitioned. DHT segments on one side of the partition receive the new key; segments on the other retain only the old key. Agents in different segments present attestations signed by different keys, causing verification failures when cross-partition communication resumes. *Mitigation:* Overlapping key validity periods (new key valid before old key expires) ensure both keys verify correctly during the transition. Verifiers should accept attestations signed by any non-revoked key within its validity window. *Recovery:* When the partition heals, key propagation completes and normal operation resumes automatically.

Attestation Expiration + Migration. An agent migrates to a new endpoint while its attestation approaches expiration. The migration succeeds (DHT record updated with new endpoint), but the attestation expires before the agent can serve requests at the new location. Verifiers reject the newly-migrated agent despite valid registration. *Mitigation:* Refresh attestations *before* migration. Operational rule: never migrate with less than 10% of attestation TTL remaining. A 30-day attestation should be refreshed by day 27; migration should complete before day 27 or wait until after refresh. *Best practice:* Migration checklists should include attestation validity verification as a precondition.

6.4 Scalability

Question: How do core operations scale with input size?

Method: Criterion benchmarks measuring parsing, canonicalization, prefix matching, and DHT key derivation.

Operation	Threshold	Actual	Status
URI parsing (typical)	< 5 μ s	3.7–4.1 μ s	Pass
URI parsing (max)	< 20 μ s	5.7–6.4 μ s	Pass
Canonical form	< 2 μ s	560–710 ns	Pass
<code>starts_with</code> (depth 5)	< 500 ns	~23 ns	Pass
DHT key derivation	< 5 μ s	0.7–4.1 μ s	Pass

Table 5: Scalability benchmark results

The key finding: all operations complete orders of magnitude faster than network latency (\sim 10ms) and LLM inference (500ms–2s). The scheme adds negligible overhead to agent interactions.

Linear scaling holds across input variations. No pathological cases were observed—parsing a maximum-length URI (512 characters) still completes in under 7 microseconds.

7 Related Work

We position the `agent://` URI scheme against four bodies of prior work, highlighting specific gaps that our approach addresses.

7.1 Agent Identity and Naming

The FIPA Agent Management Specification defines agent-identifiers containing names and addresses [FIPA(2004)]. While FIPA recognized the need for agent identity, it did not separate naming from addressing. The Directory Facilitator provides capability-based discovery but assumes a single platform—cross-platform federation requires explicit DF cooperation, which scales poorly [Denegri and Simari(2007), Bellifemine et al.(2007)]. Our scheme provides what FIPA intended but could not deliver: stable identity across platforms.

The A2A protocol identifies agents by their Agent Card URI [Linux Foundation(2025)]. While A2A addresses modern interoperability needs, Agent Card identity remains URI-dependent. Our scheme can interoperate with A2A by including Agent Card endpoints in registration records while maintaining a stable URI identity. A2A provides the communication layer; we provide the identity layer underneath.

Decentralized Identifiers (DIDs) provide generic decentralized identity without capability semantics [Sporny et al.(2022)]. A DID identifies an entity but says nothing about what that entity can do. Our capability path fills this gap. An agent URI could be viewed as a specialized DID with built-in capability description and discovery mechanism. Where DIDs are general-purpose, we are agent-specific—and that specificity enables capability-based discovery that generic DIDs cannot support.

7.2 Agent Discovery and Directory Services

The Contract Net Protocol [Smith(1980)] enables capability-based task allocation through manager-contractor negotiation. This protocol assumes agents can already communicate—it does not address how the manager discovers potential contractors in the first place. Our scheme provides the discovery layer that Contract Net requires.

DNS-SD and mDNS [Cheshire and Krochmal(2013), Lynn and Cheshire(2015)] work for local networks but do not scale to internet-wide agent discovery. Our DHT-based approach provides comparable semantics (service type as capability path) at global scale.

Service mesh discovery systems like Consul [HashiCorp(2023)] provide infrastructure-level discovery with health checking. These systems discover services, not agents with capabilities. Our scheme adds semantic capability matching that infrastructure discovery cannot provide.

7.3 Decentralized Systems

We adopt Kademlia’s $O(\log N)$ lookup guarantees directly [Maymounkov and Mazières(2002)]. Our contribution is the key derivation scheme that maps trust-scoped capability paths to DHT keys, enabling semantic discovery over a content-addressed substrate.

Hewitt’s actor model provides location transparency—actors communicate by reference without knowing physical location [Hewitt et al.(1973), Agha(1986)]. Our scheme brings this property to internet-scale agent systems. The agent URI is an actor reference; resolution finds current location.

The libp2p networking stack provides Kademlia implementation and peer discovery [Protocol Labs(2023)]. Our reference implementation builds on libp2p for DHT operations, demonstrating practical integration.

7.4 Trust and Attestation

The W3C Verifiable Credentials data model provides general-purpose attestation [Sporny et al.(2025)]. Our PASETO tokens are a specialized form: the issuer is the trust root, the subject is the agent URI, and the claims include capability paths. We adopt VC’s conceptual model with agent-specific semantics.

Dennis and Van Horn’s capability model treats capabilities as unforgeable tokens granting specific permissions [Dennis and Van Horn(1966), Miller et al.(2003)]. Our capability paths are descriptive (what the agent can do) rather than authoritative (permission to do it). The attestation token is the authoritative element, binding the descriptive path to organizational endorsement.

Sabater and Sierra survey computational trust and reputation models [Sabater and Sierra(2005)]. Our trust model is institutional rather than behavioral: trust roots are organizations making formal attestations, not agents accumulating reputation scores. This matches enterprise deployment patterns where organizational accountability matters [Ramchurn et al.(2004)].

7.5 Summary Comparison

Table 6 summarizes how existing approaches address the requirements from Section 2.3.

No existing approach satisfies all requirements. FIPA DF provides capability semantics but centralizes control. A2A addresses interoperability but binds identity to URI endpoints. DIDS provide decentralized identity but lack capability discovery. DNS-SD and Consul are infrastructure-level, not agent-level. The `agent://` scheme is the first to address all five requirements in an integrated design.

Approach	R1	R2	R3	R4	R5
	Topology	Capability	Decentral.	Scoping	Verifiable
FIPA DF	No	Yes	No	No	No
A2A Protocol	No	No	No	No	No
DIDS	Yes	No	Yes	No	Partial
DNS-SD	No	Yes	No	No	No
Consul	No	Partial	No	No	No
agent:// (ours)	Yes	Yes	Yes	Yes	Yes

Table 6: Requirement satisfaction by approach. R1: topology independence; R2: capability-based discovery; R3: decentralized resolution; R4: organizational scoping; R5: cryptographically verifiable claims.

8 Discussion and Limitations

8.1 Deployment Walkthrough

The invoice-approval agent introduced in Section 1 provides a concrete example of the `agent://` scheme operating through its complete lifecycle.

1. Creation. Acme Corp provisions an invoice approval agent, generating TypeID `agent_01h455vb4pex5vsknk084sn02q`. The full URI becomes [agent://acme.com/workflow/approval/invoice/agent_01h455vb4pex5vsknk084sn02q](https://acme.com/workflow/approval/invoice/agent_01h455vb4pex5vsknk084sn02q).

2. Attestation. Acme’s trust root issues a PASETO token binding the agent to capability path `/workflow/approval/invoice` with 30-day expiration. The attestation’s `capabilities` claim authorizes registration at this path and descendants.

3. Registration. The agent registers at the DHT key derived from `SHA256("acme.com" || "/" || "workflow/approval/invoice")`, storing its current endpoints (<https://agents.acme.com/v1/approvals>) and attestation token.

4. Discovery. Partner organization Globex queries for `/workflow/approval` under `acme.com`. The DHT returns registration records for all agents at that path and descendants, including Acme’s invoice approval agent.

5. Verification. Globex fetches Acme’s public key from <https://acme.com/.well-known/agent-keys.json>, verifies the attestation signature, confirms the `capabilities` claim covers `/workflow/approval/invoice`, and checks expiration. Verification succeeds; the agent is trusted.

6. Interaction. Globex’s procurement agent sends an invoice approval request to the discovered endpoint. The agents communicate using A2A or other protocols; the `agent://` URI provided stable identity for discovery.

7. Migration. Six months later, Acme migrates to a new cloud provider. The agent updates its DHT record with the new endpoint (<https://agents-new.acme.com/v1/approvals>). The URI remains unchanged. Globex’s cached reference still resolves—to the new endpoint.

8. Attestation Refresh. At day 25, the agent requests a fresh attestation from Acme’s trust root. The old attestation remains valid until day 30; the new attestation is valid for the next 30 days. No service interruption occurs.

This lifecycle demonstrates topology independence (step 7), capability-based discovery (step 4), and cryptographic verification (step 5) working together in a realistic enterprise scenario.

8.2 When to Use Agent URIs

The `agent://` URI scheme is most valuable when:

Migration is expected. If agents will move between cloud providers, scale across regions, or outlive their original infrastructure, stable identity prevents reference breakage.

Cross-organization discovery is required. If agents from multiple trust roots must interact, DHT-based discovery with explicit trust scoping enables federation without centralized registries.

Auditability matters. If audit logs must reference the same agent across time and infrastructure changes, stable URIs provide consistent identification.

Capability verification is needed. If agents' capability claims must be cryptographically verified rather than self-declared, the attestation model provides this assurance.

8.3 Limitations

Trust root infrastructure required. Organizations must operate trust root infrastructure: key management, attestation issuance, well-known endpoint hosting. This is comparable to operating a certificate authority for TLS, but adds operational burden.

DHT participation incentives. The scheme relies on DHT nodes storing and serving registration records. Why would operators run DHT nodes?

Three incentive models apply:

1. **Reciprocity-based.** Nodes only serve queries from peers who also serve them (tit-for-tat). BitTorrent's Mainline DHT demonstrates this model's viability at scale: millions of nodes participate because reciprocity is enforced at the protocol level.
2. **Stake-based.** Trust roots stake reputation or deposit to participate; misbehavior (dropping queries, serving false records) forfeits stake. This requires a coordination layer beyond the base DHT protocol.
3. **Utility-derived.** Organizations participate because discovery of their own agents requires DHT presence. If you want others to find your agents, you must contribute to the network that enables discovery. IPFS demonstrates this model: organizations running IPFS gateways gain discoverability for their content.

The specification does not mandate an incentive model—this is a deployment-time policy choice. For enterprise deployments, utility-derived incentives may suffice (organizations have business reasons to be discoverable). For open deployments, reciprocity or stake mechanisms may be needed to prevent free-riding. This is an underspecified aspect of the design, noted as future work.

No global capability ontology. Each trust root defines its own capability namespace. If `acme.com/workflow/approval` and `globex.com/process/authorize` denote the same capability, cross-organization discovery fails silently—queries find only exact path matches.

This is intentional: avoiding global governance prevents political capture and governance bottlenecks. However, it limits plug-and-play federation.

A lightweight coordination mechanism could address this: *Capability Mapping Services*. Third parties (industry consortia, standards bodies) publish equivalence mappings:

```
{  
  "acme.com/workflow/approval": [  
    "globex.com/process/authorize",  
    "initech.com/approvals/workflow"  
  ]  
}
```

Requesters consult mapping services to expand queries across equivalent paths. No global ontology is required; mappings are opt-in and domain-specific. This approach has advantages over a global ontology: domain expertise stays with domain experts, there is no governance

bottleneck, and the system degrades gracefully (works without mappings, better with them).

Mapping Service Discovery. How does a requester discover relevant mapping services? We propose a layered approach: (1) Trust roots optionally publish their own mappings at a well-known endpoint: `https://{{trust-root}}/.well-known/capability-mappings.json`. (2) Trust roots may reference third-party mapping services they endorse. (3) Industry registries (analogous to CA certificate lists) can aggregate mapping services for specific domains—healthcare, finance, logistics—providing curated equivalences for their communities.

Conflict Resolution. When multiple mapping services provide conflicting information (mapping service A says path X equals Y, mapping service B says X does *not* equal Y), resolution follows requester policy. If mappings agree, union semantics apply: query all equivalent paths and merge results. If mappings contradict, the requester decides which mapping service to trust for their use case. This is a feature, not a bug: different communities may legitimately have different equivalence judgments, and no global authority should override local domain expertise.

Standardizing capability mapping service discovery and format is noted as future work.

DHT poisoning risk. Malicious actors could register fake agents at popular capability paths. Attestation verification filters invalid registrations, but verification requires fetching keys from potentially malicious trust roots. Rate limiting and proof-of-work could mitigate but are not specified.

8.4 Future Work

Privacy-preserving discovery. Can agents register capabilities without revealing identity until matched? Commitment schemes and onion routing could enable this, but tension with attestation verification remains.

Capability ontology standardization. A shared vocabulary for common capabilities would improve cross-organization interoperability. Who maintains such an ontology and how it evolves are open governance questions.

Integration with A2A. The A2A protocol is gaining adoption [Linux Foundation(2025)]. A2A Agent Cards contain an `endpoints` field with service URIs for communication. We propose extending Agent Cards with an `agent_uri` field providing stable identity:

```
{
  "name": "Invoice Approval Agent",
  "agent_uri": "agent://acme.com/workflow/approval/agent_01h...",
  "endpoints": [
    {"url": "https://agents.acme.com/v1/approval", "protocol": "https"},
    {"url": "grpc://agents.acme.com:50051", "protocol": "grpc"}
  ],
  "attestation": "v4.public.eyJpc3MiOiJhY21lLmNvbSIs..."
}
```

The integration flow: (1) Requester discovers agents via `agent://` URI resolution, obtaining DHT records. (2) Records include Agent Card URI or embedded Agent Card. (3) Agent Card provides current endpoints (HTTPS, gRPC, WebSocket) for communication. (4) Attestation token in the Agent Card enables capability verification.

A2A provides communication semantics (how to talk to agents); the `agent://` scheme provides identity semantics (which agent you're talking to). The combination yields stable identity with flexible transport—agents can update endpoints without breaking identity references.

Specifying this integration formally and building reference implementations would accelerate practical deployment.

9 Conclusion

Agent systems today suffer from a fundamental architectural flaw: identity is bound to location. When agents migrate, references break. When organizations federate, discovery requires centralized coordination. When capabilities must be verified, self-declaration is the only option.

The `agent://` URI scheme addresses these problems through principled separation of concerns. The trust root establishes organizational authority. The capability path describes what the agent does. The agent identifier provides stable, sortable reference. Together, these components create topology-independent identity with built-in capability semantics.

DHT-based discovery enables finding agents by what they do, not where they are. Trust-root scoping prevents cross-organization pollution while permitting explicit federation. PASETO attestation binds capability claims to cryptographic verification, moving beyond self-declaration to institutional accountability.

Our evaluation demonstrates that these properties hold in practice. The capability grammar achieves 100% coverage on real-world tools. Discovery achieves perfect precision and recall across 10,000 agents. Identity provably survives migration. All operations complete in microseconds.

The `agent://` URI scheme provides a formally-specified, practically-evaluated foundation for decentralized agent identity. Like DNS separated network names from addresses, enabling the internet we know today, we believe capability-addressed agent identity can enable the multi-agent systems of tomorrow.

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