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Design of Scalable Interface Contracts in Multi-Hospital Telehealth Ecosystems

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ABSTRACT

Interface contracts are formal agreements that specify the schemas, semantics, security, quality-of-service (QoS), error-handling, audit, and versioning rules governing interactions among distributed system components. In multi-hospital telehealth ecosystems, where heterogeneous electronic health record (EHR) systems, imaging platforms, and remote patient monitoring devices must interoperate, such contracts must scale both at runtime and organizationally. This manuscript presents a framework for defining, governing, and enforcing interface contracts at scale. We define what a telehealth interface contract contains (schemas, terminology bindings, authentication and authorization, latency and availability targets, error and retry rules, audit requirements, and versioning policy) and express it in a policy-driven YAML specification language. A reference architecture combines a versioned contract registry, a validation and compatibility service, Apache Camel gateways, and a governed onboarding workflow, supported by design principles for schema evolution, deprecation timelines, and automated conformance and contract testing in CI pipelines. We compare the approach with HL7 FHIR profiles, IHE profiles, OpenAPI, and consumer-driven contract testing (Pact), and discuss governance, clinical safety review, privacy and consent, outage resilience, and cost. Evaluation uses a discrete-event simulation of up to 50 heterogeneous hospital nodes against point-to-point and FHIR-only baselines, together with a parametric effort model. At baseline load all architectures sustained about 10 requests/s per node with a median end-to-end latency of 355–370 ms; the contract layer added roughly 9–15 ms. During a simulated endpoint outage, requests failing after retries fell from about 20% to under 0.1% (median of runs), while every architecture saturated at 1.8× load. Differences in defect and violation rates at baseline load follow from stated modelling assumptions and require field validation. We state limitations and recommend multi-site pilots, an open reference implementation, and shared contract repositories.

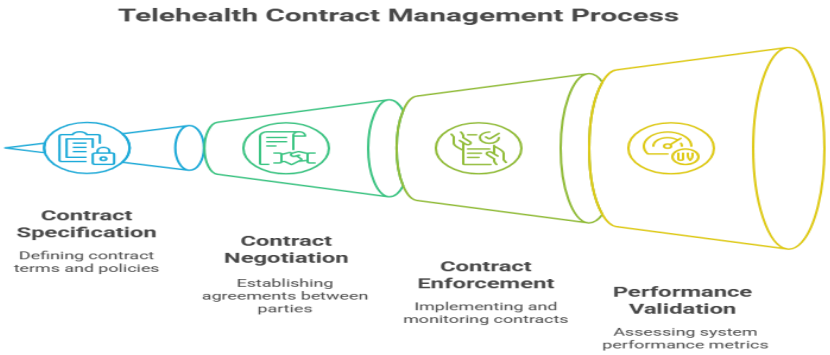

Figure-1.Telehealth Contract Management Process

Keywords : Interface Contracts, Telehealth Interoperability, Multi-Hospital Ecosystems, Service-Level Agreements, Scalability

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INTRODUCTION

The rapid adoption of telehealth modalities—remote patient monitoring, virtual consultations, teleradiology—has transformed how healthcare services are delivered, especially across geographically distributed hospital networks. While telehealth promises improved access, reduced costs, and enhanced patient engagement, realizing these benefits at scale across multiple hospitals poses significant technical and organizational challenges. Each hospital typically maintains its own EHR platform, imaging repositories, and communication infrastructure. Moreover, regulatory frameworks such as the Health Insurance Portability and Accountability Act (HIPAA) in the United States and the European Union's General Data Protection Regulation (GDPR) impose stringent requirements on data privacy, security, and auditing. To interconnect these disparate systems effectively, it is insufficient to merely expose RESTful or SOAP-based APIs; one must define **interface contracts** that precisely capture the semantics of data exchange, the performance and reliability guarantees expected, and the security and compliance policies to enforce.

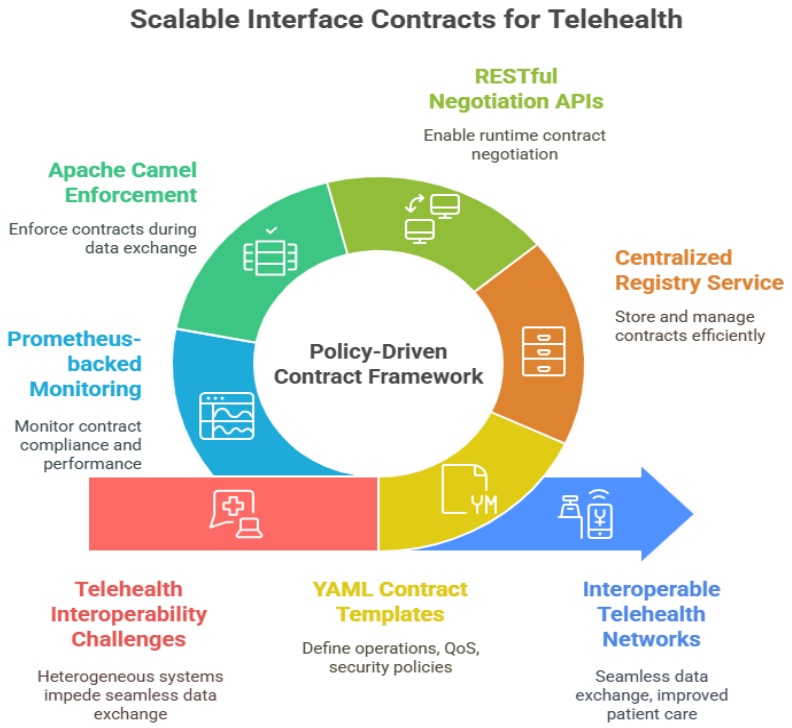

Figure-2.Scalable Interface Contracts for Telehealth

Interface contracts trace their lineage to "design by contract" in object-oriented programming, where preconditions, postconditions, and invariants ensure component correctness. In distributed systems, contracts have evolved into service-level agreements (SLAs) that include data schemas (XML Schema, JSON Schema), operational semantics (WSDL), and QoS parameters (WS-Policy). However, telehealth ecosystems require a more integrated approach: blending formal schema definitions with QoS targets, error handling policies, security directives, and mechanisms for dynamic negotiation and version evolution. Without such a unified model, ad hoc interface definitions lead to brittle integrations, frequent compatibility failures, and manual coordination overhead that undermines uptime and clinical effectiveness.

This manuscript makes six contributions. First, we present a requirements analysis based on semi-structured interviews with clinical IT stakeholders from three large hospital consortia, highlighting schema heterogeneity, evolving clinical workflows, variable network conditions, and compliance imperatives. Second, we survey existing contract specification approaches—from foundational component-based research (Meyer's design by contract, Szyperski's component software) to healthcare interoperability standards (HL7 FHIR, IHE profiles,

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ISO/IEEE 11073) and API tooling (OpenAPI, consumer-driven contract testing with Pact)—and compare them with the proposed framework (Table-2). Third, we define the contents of a telehealth interface contract (Table-1) and propose a policy-driven, YAML-based specification language that unites functional definitions, QoS directives, security and privacy policies, and versioning metadata. Fourth, we present a reference architecture—contract registry, validation service, enforcement gateways, and onboarding workflow—together with design principles for scalability: schema evolution rules, deprecation timelines, and automated conformance and contract testing in CI pipelines. Fifth, we evaluate the design by simulation with heterogeneous node profiles against point-to-point and FHIR-only baselines, measuring latency, throughput, message failures, integration defects, and resilience under load and outage, and with a parametric model of onboarding and change effort. Sixth, we address governance, clinical safety review, privacy and consent, resilience, and cost, state the limitations of the evidence, and outline a pilot roadmap.

By uniting schema, policy, QoS, and versioning in a single contract model, our framework bridges the gap between theoretical contract research and practical telehealth deployments. The rest of this manuscript details our literature review, methodology, results, and conclusions, offering a roadmap for healthcare systems aiming to build interoperable, resilient telehealth ecosystems across institutional boundaries.

In this research, an interface contract is defined as a structured agreement governing data schemas, clinical terminology mappings, operational semantics, authentication and authorization controls, service-level expectations, error recovery procedures, audit requirements, and version management policies between telehealth participants. Such contracts establish a consistent interoperability framework across heterogeneous hospital systems while reducing integration complexity. Table-1 lists the seven elements a contract contains, where each is represented in the specification language, and how each is checked.

Table-1.Elements of an interface contract in the proposed framework

Contract element	What the contract specifies	YAML section	How it is checked or enforced
Schemas	Operation signatures; JSON Schema for request and response payloads, including required fields, data types, and cardinality	Functional	CI schema validation; per-message validation at the gateway
Semantics and terminologies	Operation pre- and postconditions; code-system and value-set bindings (e.g., LOINC, SNOMED CT, UCUM units); references to FHIR or IHE profiles where used	Functional	CI terminology-binding check; clinical test vectors; code validation at the gateway
Authentication and authorization	Required identity assertion, OAuth2 scopes, mutual TLS, consent and role preconditions	Policy	Policy enforcement at the provider gateway
Latency and availability targets	Median and tail latency objectives, per-request deadline, availability target, minimum throughput	QoS	Gateway timers; Prometheus SLO alerts; CI smoke tests
Error and retry rules	Error taxonomy (retryable or not), maximum retries, backoff, timeouts, fallback endpoints, circuit-breaker thresholds, message criticality	Policy	Camel routes; fault-injection tests in CI
Audit requirements	Events to log, retention period, contract version recorded per message, access trail	Policy	Gateway audit log; periodic audit review

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Versioning policy	Semantic version, effective date, backward-compatibility flag, deprecation window, successor reference	Versioning	CI breaking-change detector; registry promotion rules

LITERATURE REVIEW

Interface contract research originates in component-based software engineering, where design by contract principles—introduced by Meyer—use preconditions, postconditions, and invariants to ensure component correctness. Szyperski's work on component software extended these concepts to binary-reusable components, stressing interface definitions and versioning. In distributed systems, service contracts evolved to include data schemas (XML Schema for SOAP, JSON Schema for REST) and QoS policies (WS-Policy, WS-SLAs) that specify performance objectives and reliability guarantees.

Healthcare interoperability standards such as HL7 v2/v3 and FHIR provide normative resource definitions, messaging paradigms, and RESTful API structures. FHIR—Fast Healthcare Interoperability Resources—offers modular clinical data models and a RESTful interface but does not natively incorporate QoS directives or error-handling policies. Implementers typically augment FHIR with custom SLA definitions or external policy engines, leading to fragmentation. ISO/IEEE 11073 standards govern point of-care device communication but focus on low-level transport and encoding rather than high-level semantic contracts.

Research on SLAs in healthcare (de la Torre Díez et al., 2018) investigates SLA monitoring for telemedicine applications but treats SLAs and data schemas separately. Studies by Ammenwerth et al. explore governance in distributed telemedicine, emphasizing organizational aspects over technical contract models. Recent blockchain-based frameworks (Li et al., 2020) propose immutable registries for access control but neglect the performance trade-offs at scale. Edge-enabled telehealth architectures (Nguyen & Pathirana, 2021) reduce latency by offloading computation to the network edge but do not address interface semantics.

A key gap in the literature is the absence of a unified contract model that integrates functional definitions, formal schemas, QoS requirements, security and compliance policies, and versioning within a single specification, alongside mechanisms for dynamic negotiation and runtime evolution. While semantic web technologies (Berners-Lee et al., 2001; De Roure et al., 2005) suggest using OWL ontologies for semantic alignment, practical healthcare deployments rarely leverage ontology-based contract compatibility checks. Similarly, formal verification techniques (Omotosho & Van Zyl, 2020) ensure contract conformance but are seldom integrated into everyday telehealth workflows.

Our proposed framework synthesizes best practices from component software research, SLA management, healthcare interoperability standards, policy-driven integration, and semantic web/ontology approaches. By doing so, it addresses scalability, clarity, and adaptability gaps in multi-hospital telehealth ecosystems, enabling robust, patient-centric telehealth services across institutional boundaries.

Table-2 compares the proposed framework with the approaches most often used to specify or test healthcare interfaces. The comparison reflects the published capabilities of each approach as understood by the authors and should be re-verified against current specifications; it is intended to show where capabilities are combined, not to suggest that the other approaches are deficient for their intended purpose.

Table-2.Comparison with existing frameworks

Capability	HL7 FHIR profiles	IHE profiles	OpenAPI	Pact	Proposed framework
Schema / data-model definition	Yes (profiles)	Yes (via referenced	Yes (JSON Schema)	Partial (example-	Yes

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Capability	HL7 FHIR profiles	IHE profiles	OpenAPI	Pact	Proposed framework
		standards)		based)	
Terminology bindings	Yes (value sets)	Partial (content profiles)	No	No	Yes*
Telehealth-specific operations	Partial	Partial	No	No	Partial (extensible)
Authentication / authorization	Partial (SMART on FHIR, separate)	Partial (IUA, ATNA)	Partial (declares security schemes)	No	Yes
Latency / availability targets	No	No	No	No	Yes
Error and retry rules	Partial (OperationOutcome; no retry policy)	Partial	Partial (documents error responses)	Partial (error responses testable)	Yes
Audit requirements	Partial (AuditEvent resource)	Yes (ATNA)	No	No	Yes
Versioning and deprecation policy	Partial (versions, maturity levels)	Partial	Partial (info.version only)	Partial (broker version tracking)	Yes
Contract registry	Partial (package and IG registries)	Partial (profile catalogs)	Tool-dependent	Yes (Pact Broker)	Yes
Automated conformance / contract testing	Partial (validators, test platforms)	Partial (Connectathon tooling)	Partial (third-party tools)	Yes (core feature)	Yes
Runtime negotiation and enforcement	Partial (CapabilityStatement discovery)	No	No	No (CI-time verification)	Yes
Governance and clinical safety workflow	Partial (standards process, not local change control)	Partial	No	No	Yes*

* Designed capability, not validated in a field deployment. The simulation reported here exercised only gateway validation overhead, retry and backoff, circuit breaking, and fallback routing.

The novelty of the framework is not any single element—most exist in isolation—but their composition in one versioned contract artifact that couples QoS, error and retry, security and consent, audit, and versioning and deprecation policies to schemas and terminology, with registry-mediated negotiation, gateway enforcement, and CI promotion gates. The framework is designed to build on FHIR and IHE profiles (referenced from the functional section), OpenAPI (as an optional syntactic description), and Pact-style tests (as the consumer-driven test gate) rather than to replace them.

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METHODOLOGY

To design and evaluate our scalable interface contract framework, we followed a four-phase methodology: (1) requirements elicitation and contract language design, (2) reference architecture and prototype implementation,

(3) design principles for scalability, and (4) evaluation by simulation and a parametric effort model.

Phase 1: Requirements Elicitation and Contract Language Design

We conducted semi-structured interviews with IT directors, integration architects, and clinical informatics specialists from three major hospital networks (each spanning 10–20 facilities). Interview questions probed current telehealth integration practices, pain points in schema mapping, SLA enforcement, error recovery workflows, and compliance auditing. Key insights included:

- **Schema Heterogeneity:** Hospitals use disparate EHR systems (Epic, Cerner, Meditech) with custom extensions; imaging platforms employ DICOM metadata variations.
- **Evolving Clinical Workflows:** Telemonitoring use cases (e.g., vital-sign streaming) frequently add new sensors or change observation sets, requiring schema flexibility.
- **Variable Network Conditions:** Rural-urban connectivity differences lead to fluctuating latencies (50–300 ms) and intermittent outages.
- **Compliance Imperatives:** Contracts must enforce encryption (TLS 1.2+), audit logging, consent checks, and data residency constraints.
- **Error-Handling Policies:** Stakeholders require formal definitions of retry logic (exponential backoff), fallback endpoints, and stakeholder notifications in case of repeated failures.

Based on these requirements, we designed a **YAML-based contract specification language** comprising four sections:

1. **Functional:** Defines operations (e.g., Submit Vitals, Request Consult), corresponding JSON Schemas for inputs/outputs (with required fields, data types, code system constraints).
2. **QoS:** Specifies performance objectives (e.g., median response time ≤ 450 ms and a per-request deadline of 800 ms for non-streaming exchange operations, 99.9% availability, throughput ≥ 50 req/s). Real-time audio and video sessions have separate media-path targets outside this contract.
3. **Policy:** Details security directives (TLS requirement, OAuth2 scopes), error-handling rules (max retries, timeout durations), and compliance checks (audit logging, consent flags).
4. **Versioning:** Includes semantic version numbers (MAJOR.MINOR.PATCH), effective dates, and backward-compatibility flags to guide consumer upgrades.

Contracts are stored in a **Contract Registry Service**, backed by a relational database, exposing RESTful endpoints for retrieval, publication, and negotiation.

An illustrative contract excerpt follows (values are examples, not recommendations).

```
contract: SubmitVitals          # illustrative values

version: 2.3.0                  # MAJOR.MINOR.PATCH
```

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```
effective: 2026-01-15
backward_compatible: true
deprecates: 1.x                # 180-day notice
functional:
  operation: POST /vitals
  request_schema: schemas/vitals-v2.json
  terminology: {observation: LOINC, unit: UCUM}
qos:
  latency_p50_ms: 450
  deadline_ms: 800
  availability: 99.9
policy:
  auth: {oauth2_scopes: [vitals.write], mtls: true}
  consent_check: required
  retry: {max: 3, backoff: exponential, base_ms: 100}
  fallback: replica-endpoint
  audit: {log_contract_version: true, retention_days: 2190}
```

Phase 2: Reference Architecture and Prototype Implementation

Reference architecture. Figure-3 separates a contract control plane from a data plane. The control plane comprises a contract authoring workspace, a CI pipeline, a validation and compatibility service that checks contracts against JSON Schema meta-schemas, policy templates, terminology bindings, and the declared version ranges of registered consumers and providers, a governance workflow for clinical safety, privacy, and approval, and the Contract Registry, which is the system of record for approved, versioned contracts and exposes the pull and push negotiation APIs. The data plane consists of Apache Camel gateways at the edge of each hospital system or service. A consumer gateway caches the contract versions it may use, checks outgoing messages for conformance, and routes to fallback endpoints. A provider gateway validates incoming messages against the active contract, enforces authentication, authorization, and consent policies, times each operation against its QoS targets, applies retry, backoff, and circuit-breaker rules, and emits metrics and audit events (including the contract version) to Prometheus/Grafana and an audit log. Because gateways operate from cached contracts, data-plane traffic can continue if the registry is temporarily unreachable.

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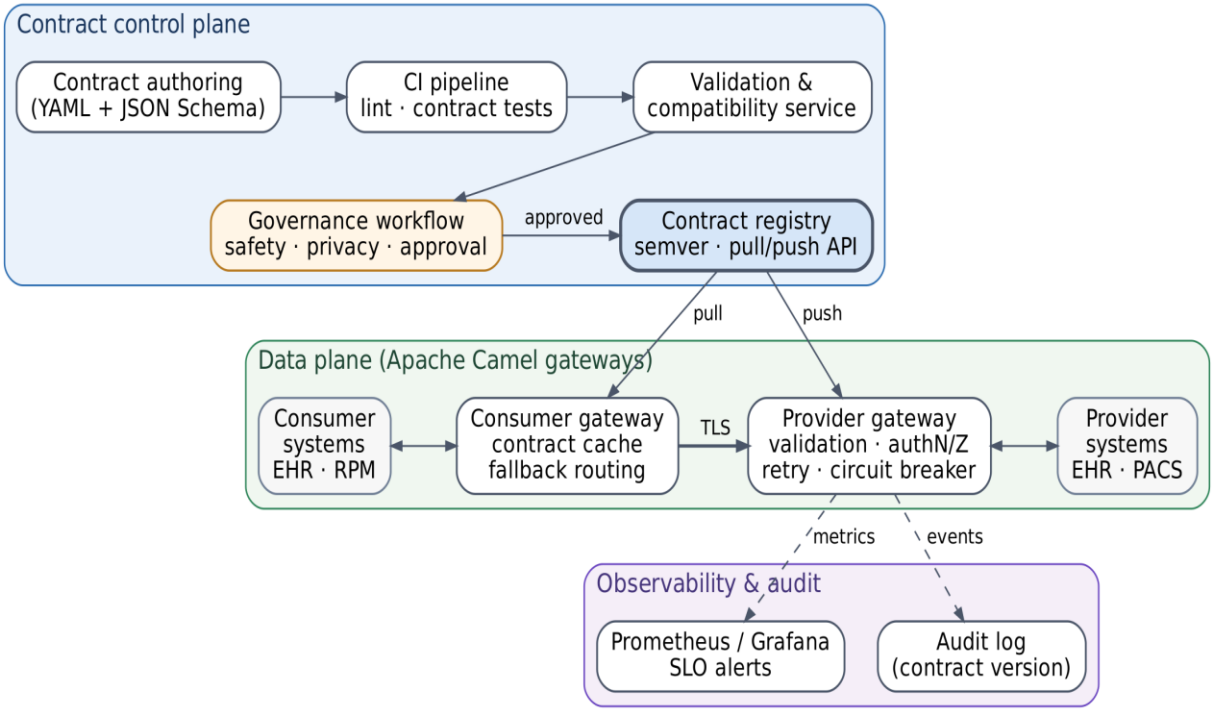

Figure-3.Reference architecture: contract registry, validation, gateways, and observability

Onboarding workflow. Figure-4 shows how a new participant or a changed contract enters service. The author drafts the contract (schemas, terminology bindings, policies). Automated checks validate the draft, test compatibility against registered parties, and run sandbox conformance and contract tests. A clinical safety and privacy/consent review and a governance board approval follow; a failure at any gate returns the contract to the author with findings. Approved contracts are published to the registry with a semantic version and effective date, rolled out through gateways as a canary, and monitored.

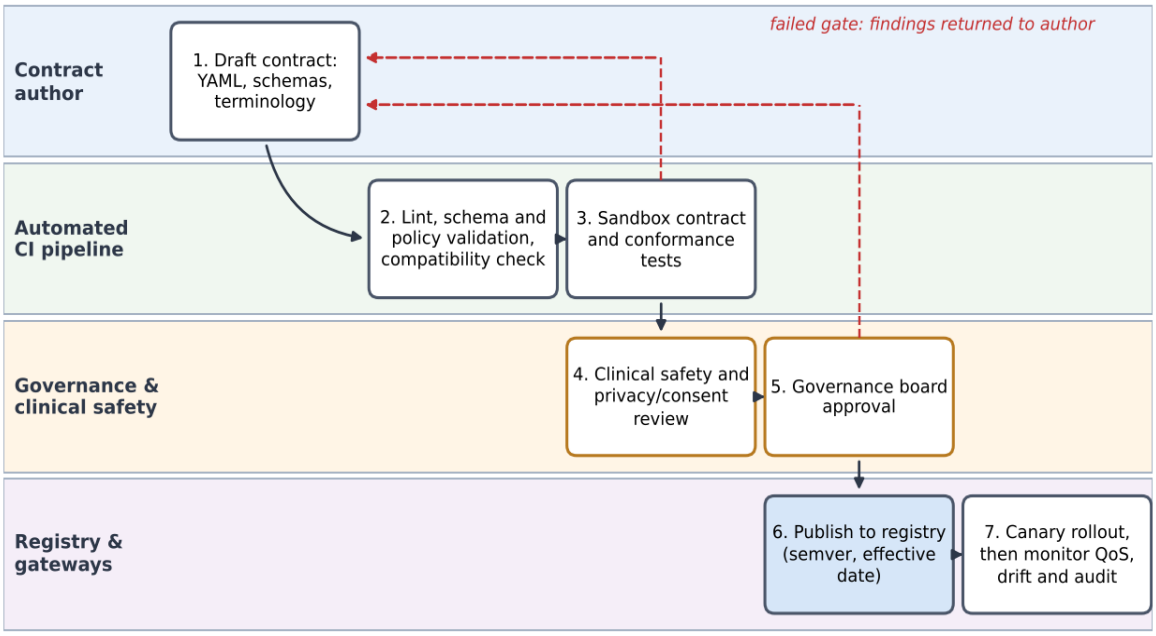

Figure-4.Onboarding and change workflow with automated gates and governance approval

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Prototype Implementation:

We implemented the registry and negotiation API using Java/Spring Boot. Contracts uploaded as YAML are validated against JSON Schemas and policy templates. The negotiation API supports:

- **Pull-based Negotiation:** Consumers request the latest contract version; the registry computes compatibility against the consumer's supported version range.
- **Push-based Negotiation:** Providers push new contract versions; consumers receive webhooks to trigger integration tests.

An **Apache Camel** integration layer enforces contracts at runtime: messages passing through Camel routes are validated against schemas, QoS metrics are monitored via embedded timers, and policy rules drive error handling (e.g., routing to fallback endpoints after retries). We integrated **Prometheus** and **Grafana** for real-time QoS monitoring and alerting on contract violations.

Phase 3: Design Principles for Scalability

Scalability has two dimensions: runtime (throughput and latency as the number of nodes grows) and organizational (effort to add a participant or change a contract as the number of participants grows). We adopt the following principles.

- **Schema evolution rules.** Within a MAJOR version only backward-compatible changes are allowed: adding optional fields, widening value ranges, or adding enumerated values that consumers must tolerate (tolerant-reader rule). Removing or renaming a field, changing a field's type or meaning, making an optional field required, narrowing a value set, or tightening QoS or security requirements requires a new MAJOR version. MINOR versions carry backward-compatible additions and PATCH versions carry clarifications without schema change. A terminology binding that moves to a superset value set is MINOR; otherwise MAJOR.
- **Deprecation timelines.** A provider supports the previous MAJOR version in parallel with its successor for a notice period that we propose to default to 180 days (configurable per consortium and to be tuned in pilots). Deprecation is announced through the registry and push webhooks. Retirement is blocked while active consumers still send traffic on the old version, unless governance approves an exception; security-critical or clinical-safety fixes may use a shortened, approved timeline.
- **Automated conformance and contract testing in CI.** Every contract change triggers a pipeline (Figure-5): lint and policy-template check; breaking-change detection against the published version; terminology-binding check; consumer-driven contract tests, in which each registered consumer publishes the subset of the contract it relies on and providers are verified against it; provider verification with synthetic messages generated from schemas; and latency, fault-injection, and security smoke tests against the declared QoS targets. A contract cannot move from Proposed to Active unless all gates pass and governance approves.
- **Enforcement at the edge, authority at the centre.** The registry is the single source of truth, but gateways enforce from cached contracts so that the registry is not on the request path.
- **Safe retries and contracts as code.** Operations are declared idempotent or not so that retries are safe; contracts and test fixtures are version-controlled and peer-reviewed like source code, and fixtures use synthetic data only.

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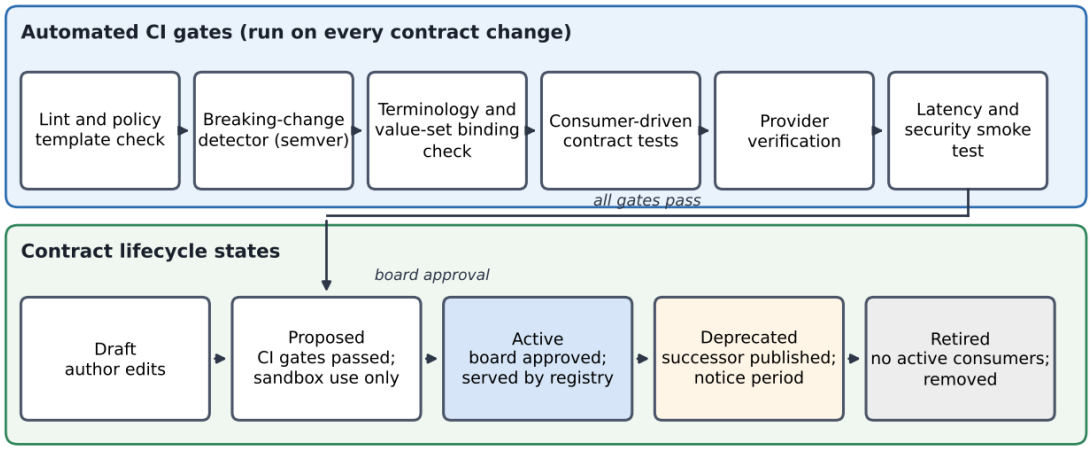

Figure-5.Automated CI gates and contract lifecycle states

Phase 4: Evaluation Design

To evaluate scalability without deploying to real hospital networks, we built a discrete-event simulation in Python using SimPy and compared the proposed framework with two baselines: point-to-point interfaces with ad hoc retry behaviour, and a FHIR-only approach in which payloads follow FHIR but QoS, retry, and fallback behaviour are left to each implementation. Because the evaluation is simulated, all behavioural parameters of the three architectures are modelling assumptions (Table-4), and the results should be read as the consequences of those assumptions, not as field measurements.

Each hospital node is one of five heterogeneous system profiles with different processing speeds and worker pools (Table-3) and generates telehealth requests with Poisson arrivals ($\lambda = 10$ req/s per node at baseline) to a randomly chosen other node. Network round-trip delay is uniform on 50–200 ms; processing time is uniform on 100–300 ms scaled by the profile factor; each node has a transient per-attempt failure probability drawn uniformly from 1–5%. A request violates its contract if it fails after retries, is rejected for a schema or semantic mismatch, or completes after the 800 ms deadline. Every scenario ran for 200 simulated seconds (30 s warm-up) with 8 independent replications; tables report mean ± 95% confidence interval (t-distribution).

Table-3.Simulated system profiles

Profile	Share of nodes	Processing-time factor	Workers per node	Mismatch factor
EHR-A (Epic-like)	30%	1.0	4	1.0
EHR-B (Cerner-like)	25%	1.1	4	1.2
EHR-C (Meditech-like)	15%	1.4	5	1.6
Imaging platform	15%	1.6	6	1.5
Remote-monitoring gateway	15%	0.6	3	1.3

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Table-4.Assumed behaviour of the three architectures (base mismatch rate is multiplied by the profile's mismatch factor)

Architecture	Gateway overhead	Schema/semantic mismatch rate	Retry policy	Fallback
Point-to-point	none	2.0%, found only after delivery	1 retry, fixed 500 ms	none
FHIR-only	3–8 ms	0.8%, found only after delivery	2 retries, fixed 500 ms	none
Proposed framework	8–20 ms	0.2%, rejected at the gateway	3 retries, exponential backoff (100 ms base)	One attempt at a replica endpoint (+100 ms WAN); circuit breaker, 5 s detection

For each scenario we collected the following metrics:

- **Goodput:** Successful requests per second.
- **Latency percentiles:** 50th, 95th, and 99th percentiles of end-to-end latency of successful requests.
- **Contract violation rate:** Percentage of requests that failed after retries, were rejected for mismatch, or completed after the 800 ms deadline.
- **Message failure rate:** Percentage of requests that failed after all retries and fallbacks.
- **Integration defect rate:** Percentage of requests rejected or failed because of schema or semantic mismatch between sender and receiver.

Simulation code logged metrics to CSV for post-processing. Beyond the runtime simulation, we model organizational effort—person-days to onboard one new hospital and to change one contract—with a simple parametric model (Table-8). Its person-day parameters are planning assumptions supplied by the authors, not measurements, and are intended to be replaced with pilot data.

RESULTS

The results below report simulation outputs under the assumptions of Table-3 and Table-4. They show how the design behaves under those assumptions and should not be read as evidence of field performance.

Baseline scaling

Table-5.Simulation results by node count (mean ± 95% CI of 8 runs; latency in ms; rates in % of requests)

Nodes	Architecture	Goodput (req/s)	p50	p95	p99	Failed after retries	Mismatch rejected	Past 800 ms	Violation
10	Point-to-point	97.5 ± 0.7	360.6 ± 0.9	600.9 ± 7.9	1286.4 ± 22.6	0.11 ± 0.01	2.54 ± 0.12	2.96 ± 0.20	5.61 ± 0.15

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10	FHIR-only	99.2 ± 0.6	365.2 ± 0.9	608.7 ± 5.9	1310.1 ± 16.0	0.01 ± 0.01	0.98 ± 0.06	3.10 ± 0.21	4.09 ± 0.24
10	Proposed	100.1 ± 0.5	374.6 ± 1.4	615.7 ± 4.6	948.0 ± 24.2	0.00 ± 0.00	0.27 ± 0.03	2.13 ± 0.17	2.41 ± 0.17
30	Point-to-point	291.6 ± 0.9	356.6 ± 0.8	599.3 ± 2.8	1269.6 ± 11.8	0.09 ± 0.02	2.54 ± 0.06	2.79 ± 0.15	5.42 ± 0.16
30	FHIR-only	297.3 ± 0.8	361.8 ± 0.9	606.8 ± 4.5	1290.2 ± 9.6	0.00 ± 0.00	1.02 ± 0.03	2.89 ± 0.16	3.91 ± 0.14
30	Proposed	299.1 ± 1.0	370.5 ± 0.6	610.7 ± 2.7	921.1 ± 11.1	0.00 ± 0.00	0.25 ± 0.02	1.83 ± 0.09	2.08 ± 0.09
50	Point-to-point	485.8 ± 0.9	355.4 ± 0.5	602.2 ± 4.0	1285.9 ± 10.4	0.10 ± 0.01	2.53 ± 0.05	2.87 ± 0.15	5.49 ± 0.16
50	FHIR-only	495.0 ± 1.5	361.5 ± 0.7	611.4 ± 5.1	1304.2 ± 7.9	0.00 ± 0.00	1.01 ± 0.03	3.03 ± 0.18	4.05 ± 0.18
50	Proposed	498.9 ± 1.6	370.1 ± 0.4	614.0 ± 3.6	944.7 ± 14.5	0.00 ± 0.00	0.25 ± 0.01	1.96 ± 0.10	2.22 ± 0.10

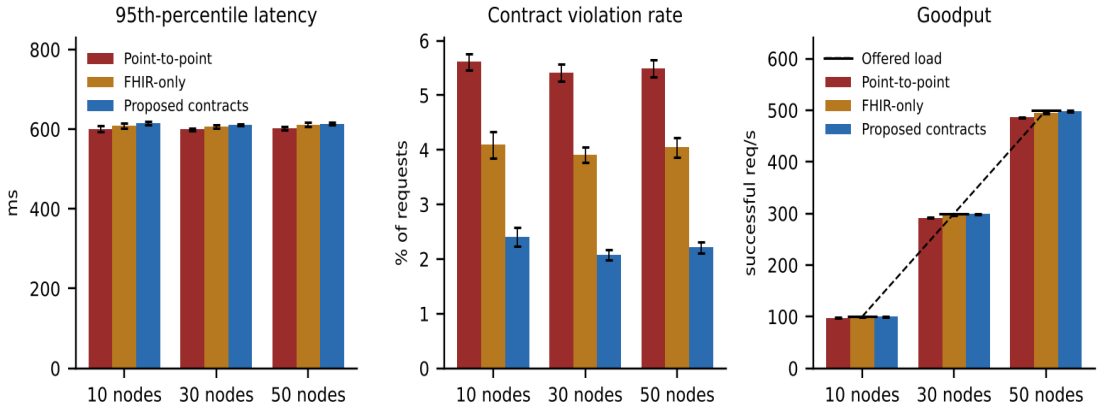

Figure-6.Latency, violation rate, and goodput by node count

Goodput rose in proportion to node count and tracked offered load for all three architectures. This is largely built into the setup, since each added node adds both load and processing capacity and the registry is not on the request path, so it should not be read as proof of scalability beyond the modelled range. At 50 nodes the median end-to-end latency was 355 ms (point-to-point), 361 ms (FHIR-only), and 370 ms (proposed), so the contract layer added about 9–15 ms at the median. The 95th percentile was about 600–615 ms for all three and roughly 2–3% of successful requests exceeded the 800 ms deadline. Median latency exceeds 300 ms in all architectures because the assumed network delay (50–200 ms) and processing time (100–300 ms) alone sum to a median above 300 ms; the contract's latency targets (a 450 ms median and an 800 ms deadline, Table-1) are set accordingly.

The proposed framework had the lowest violation rate (2.2% at 50 nodes versus 4.0% for FHIR-only and 5.5% for point-to-point), the lowest mismatch rate seen by receivers, and a lower 99th percentile, and message failures after retries were near zero for the FHIR-only and proposed designs. These differences follow directly from the defect rates and retry policies assumed in Table-4. In a parity control in which all three architectures were given identical mismatch rate and retry behaviour, with only gateway overhead differing, violation rates were 2.1%, 2.2%, and 2.2% respectively, with no advantage for the proposed design. The advantage reported

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in Table-5 is therefore an assumption about the benefit of pre-flight validation and disciplined retry, which field pilots must test.

Gateway overhead sensitivity

Because gateway overhead is a key uncertain parameter, we varied the mean validation and enforcement overhead of the proposed framework from 10 to 100 ms (50 nodes).

Table-6.Sensitivity of the proposed framework to gateway overhead (mean ± 95% CI; latency in ms; violation in %)

Gateway overhead	p50	p95	Violation
10 ms (mean)	366.1 ± 0.6	609.9 ± 4.6	2.17 ± 0.12
25 ms (mean)	380.9 ± 0.6	624.1 ± 5.2	2.28 ± 0.15
50 ms (mean)	405.9 ± 0.5	649.6 ± 3.5	2.51 ± 0.12
100 ms (mean)	455.9 ± 0.5	700.1 ± 4.5	2.95 ± 0.14

Median latency grew roughly in step with the overhead and violations rose modestly (past-deadline requests), indicating that moderate overheads are tolerable for non-streaming operations but that overhead should be budgeted explicitly in the contract's latency target.

Stress and outage resilience

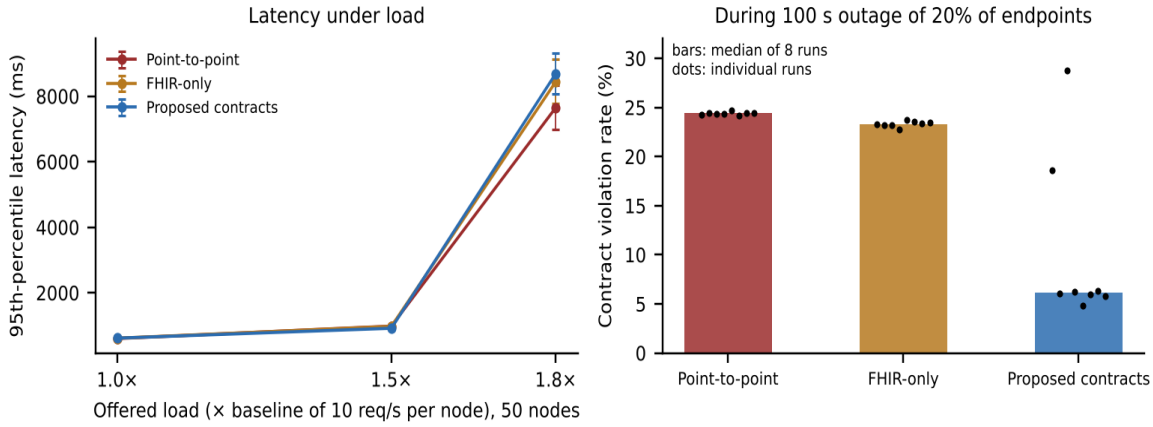

Figure-7.Latency under increasing load (left) and violation rate during an endpoint outage (right)

Under 1.5× offered load all architectures remained functional but with markedly higher tail latency. At 1.8× load every architecture saturated: the 95th-percentile latency exceeded 8 s and about 59–60% of requests violated their contract, with no meaningful difference between designs. The contract layer does not add capacity, and capacity planning remains necessary.

In the outage scenario, 20% of endpoints (10 of 50) were unreachable for 100 s. The median share of requests that failed after retries was 19.8% for point-to-point and 19.6% for FHIR-only, versus 0.01% for the proposed design, whose circuit breaker and replica fallback redirected traffic after a 5 s detection delay (Table-7). Median violation rates were 24.4%, 23.3%, and 6.1%. Results for the proposed design varied widely across

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runs (from 4.8% to 28.7%): the two worst runs (18.6% and 28.7%) were those in which half or more of the endpoints of one system type were down, leaving few healthy replicas. Fallback therefore depends on replica capacity. The simulation did not model a registry outage, which the design addresses by contract caching but which remains to be tested.

Table-7.Outage scenario, 50 nodes, 20% of endpoints down for 100 s (median and range of 8 runs; % of requests)

Architecture	Failed after retries (median)	Violation (median)	Violation (range)
Point-to-point	19.83	24.4	24.2–24.7
FHIR-only	19.56	23.3	22.8–23.8
Proposed	0.01	6.1	4.8–28.7

Onboarding and change effort

Table-8 and Figure-8 apply the parametric effort model described in the methodology. For point-to-point integration, onboarding effort grows with the number of existing systems because each requires its own interface; with FHIR-only it grows more slowly; with the contract framework there is a higher fixed cost (authoring, registry, gateway setup) and a small per-system cost. The shaded band shows the proposed framework with its effort parameters halved and doubled. The crossover therefore occurs at only a few connected systems under our assumptions, but all person-day values are illustrative assumptions, not measurements, and must be replaced with pilot data.

Table-8.Modelled effort in person-days (planning assumptions, not measurements); N = existing connected systems, k = consumers affected by a change (taken equal to N)

N, k	Onboard: point-to-point	Onboard: FHIR-only	Onboard: proposed	Change: point-to-point	Change: FHIR-only	Change: proposed
5	40	22	15.2	25	14.5	5
10	80	32	16.5	50	27.0	7
25	200	62	20.2	125	64.5	13
50	400	112	26.5	250	127.0	23

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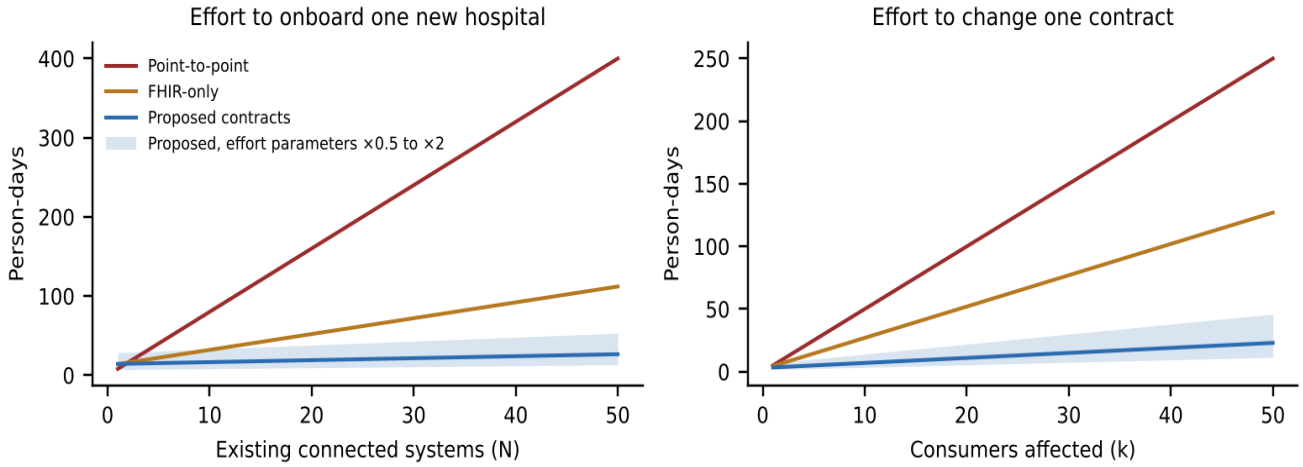

Figure-8.Modelled onboarding effort and contract-change effort (planning assumptions)

Qualitative Feedback

In follow-up workshops with mock integration teams, participants reported that the policy-driven contract syntax improved clarity around expected data formats, QoS guarantees, and error-handling procedures, and estimated that integration time decreased by about 30% compared with ad hoc API specifications. This is a self-reported estimate from a small, uncontrolled group; it is not a measured result and is not used elsewhere in this evaluation.

Governance, Clinical Safety, Privacy, Resilience, And Cost

Governance

Contracts are shared artifacts and need explicit ownership. We propose that each contract has a named provider owner; that a consortium contract board, including integration architects, clinical informatics, security, and privacy representatives, approves MAJOR changes, while MINOR and PATCH changes follow a lighter delegated path once automated gates pass; that review service levels and an escalation route for disputes are agreed in advance; and that an emergency path exists for security or patient-safety fixes, with retrospective review. Decisions, approvals, and the version history are kept in the registry as an audit trail.

Clinical safety review

Any contract change that affects clinical content (for example a changed unit, code system, or observation set) is assessed under the participating organizations' clinical risk management process, using hazard analysis in the spirit of ISO 14971, before promotion to Active. The workflow therefore includes a clinical safety reviewer, risk-based change classes (cosmetic, additive, behaviour-changing), clinical test vectors in the CI suite, canary rollout with the ability to roll back to the previous version, and monitoring of semantic drift. Passing automated gates is necessary but not sufficient for approval.

Privacy and consent

Contracts and test fixtures contain no patient data; fixtures are synthetic. Contracts declare the consent and authorization preconditions each operation requires (consent flags, purpose of use, role scopes), the minimum necessary data elements, data-residency constraints, encryption requirements (TLS 1.2 or later), and retention periods for audit records, supporting HIPAA and GDPR obligations. Provider gateways check consent at request time; delays in propagating revoked consent, and cross-jurisdiction consent semantics, are open issues

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for pilots. Audit logs record the contract version and decision for each message without storing clinical payloads.

Resilience during outages

Gateways run from locally cached, signed contract versions so that a registry outage stops publication and negotiation of new versions but not exchange under existing ones. Retries use bounded exponential backoff and idempotency declarations, circuit breakers stop repeated calls to failed endpoints, and contracts name fallback endpoints and a criticality class that determines whether messages are queued, rerouted, or escalated to clinical staff for manual workflows during prolonged downtime. The simulation exercised endpoint outages only; registry outages, queue durability, and downtime procedures need live testing.

Cost

Costs of the approach are the registry and gateway infrastructure and its operation, CI tooling and test maintenance, governance staffing (board, clinical safety, and privacy reviews), authoring and training for contract owners, and the overhead per message at gateways. Expected savings are reduced effort per integration and per change, fewer integration defects, and less downtime from incompatible changes. We have not measured these costs. The effort model in Table-8 suggests the savings grow with the number of connected systems, but whether they exceed the fixed and governance costs for a given consortium is an empirical question for pilots that should record effort, defects, and incidents against the current process.

Limitations

The evidence presented has several limitations. First, the evaluation is simulated, not run on real hospital systems: network, processing, failure, and defect behaviour are modelled with simple distributions, and the advantages of the proposed design at baseline load arise from assumed defect rates and retry policies (the parity control shows no advantage when these are equalized). Second, the largest scenario has 50 nodes and a short horizon; linear throughput scaling in this range should not be extrapolated to larger networks, and the model does not capture registry load, contract-cache invalidation at scale, or correlated failures. Third, the simulation does not model human governance delays, on-premises security proxies, real payload sizes, or streaming media. Fourth, the effort comparison rests on assumed parameters and the 30% integration-time figure is a self-reported estimate from a small group. Fifth, the interview study informed requirements but is not a quantitative evaluation, and the comparison in Table-2 reflects our reading of the published capabilities of the other approaches. Finally, the prototype does not yet implement every element of Table-1 (for example, terminology-binding checks and full consent propagation).

CONCLUSION

This manuscript presents a policy-driven framework for designing interface contracts for multi-hospital telehealth ecosystems. It defines what such a contract contains, specifies it in a single versioned YAML artifact that unites schemas and terminology, QoS, security and consent, error handling, audit, and versioning, and supplies a reference architecture, schema-evolution and deprecation rules, CI-based conformance and contract testing, and a governed onboarding workflow. In simulation with up to 50 heterogeneous nodes, the contract layer added about 9–15 ms of median latency and, under the assumptions stated, reduced failures after retries during endpoint outages from about 20% to under 0.1%. Differences in baseline violation rates depend on assumed defect rates, all architectures saturated at 1.8× load, and the effort savings are modelled, not measured. The results justify field evaluation but do not establish scalability or clinical effectiveness.

Recommendations and Future Work:

- **Pilots across real hospital networks:** Conduct staged pilots across several hospitals and EHR vendors to measure onboarding time, integration defects, message failures, latency and throughput under

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production load, and governance overhead against the existing process, including a registry-outage exercise.

- **Open reference implementation and shared contract repositories:** Publish an open reference implementation of the registry, validator, and gateways with sample contracts, and host shared, versioned contract repositories for consortia so that contracts for common operations (vital signs, consults, imaging requests) can be reused and compared.

- **Semantic web integration:** Evaluate OWL ontologies to automate semantic compatibility checks, enabling alignment of clinical concepts (e.g., LOINC, SNOMED CT).

- **Governance and safety workflows:** Integrate contract approval, clinical safety, and audit workflows into enterprise architecture and compliance tooling, and measure review time and effectiveness.

- **Adaptive contracts and tamper-evident registries:** Investigate runtime contract adaptation from monitored QoS trends and, where cross-jurisdiction provenance is required, whether blockchain-backed or other tamper-evident registries justify their performance and operational cost compared with a signed, audited conventional registry.

By defining contracts precisely, governing their evolution, and testing them continuously, healthcare organizations may be able to federate telehealth services across institutional boundaries more reliably; whether this holds in practice is the question pilots should answer.

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