DFA-based Policy Validation in BGP-Routed Credit Transfer Networks

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Abstract

Massive Open Online Courses (MOOCs) have made education easily accessible, but the inter-university credit transfer process that is both scalable and policy compliant is difficult to implement. This research work presents a novel DFA-based Policy Validation in BGP-Routed Credit Transfer Networks approach using BGP-based routing combined with DFA-based policy validation. Here, Universities will be treated as autonomous systems forming part of a distributed academic federation system, where routing identifies optimal routes for credit transfer based on course equivalency and credit weight. A multi-stage DFA engine checks the satisfaction of prerequisites, accreditation compliance, and credit equivalence. JDBC-SQL integration along with two-phase commit mechanism is used to maintain database consistency. The proposed implementation using Java, MySQL, JDBC, ANTLR4, and FRR was tested on 100 interconnected university nodes. It showed 96.3% of validation efficiency, 99.7% of transaction consistency, 23.4 ms average latency, and 812 requests per second, which indicates superior performance of the proposed method against the traditional centralized and blockchain-based methods.

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1. Introduction

The emergence of MOOCs has revolutionized the process of higher education by facilitating the provision of educational content as well as acquisition of course credits from different universities all over the globe. The increased popularity of online learning systems has provided new options for academic mobility and offered learners an opportunity to obtain information that is not limited by a specific university. Nevertheless, the issues related to the transfer and validation of the acquired credits are complicated due to the differences in the regulations of different institutions, accreditation procedures, prerequisites, grading policies, and courses' equivalency. The majority of current credit transfer approaches are based on the manual assessment of the credits, creation of centralized databases, or the existence of agreements between institutions.

In order to solve these issues, a distributed system of academic credit transfer is proposed, which is based on ideas from inter-domain routing and formal verification of policies. Within this proposed approach, universities are viewed as independent entities that can independently operate with their academic policies but at the same time engage into the network of cooperative academic credit transfer. A policy-aware routing system that is built using ideas of the Border Gateway Protocol (BGP) is employed in order to find valid paths for transfer of academic credits on the basis of course equivalence, accreditation compatibility and policy compliance. In contrary to existing centralized approaches, the proposed model allows to make decentralized decisions.

The proposed framework utilizes the integration of BGP-based routing, DFA-based validation, JDBC-based distributed database management and 2PC coordination mechanism in order to provide secure and consistent credit transfer. Specifically, the BGP component determines the best transfer routes, while the DFA validator checks the lexically, syntactically and semantically the institutional policies, necessary preconditions and equivalence of courses. On the other hand, the JDBC-SQL framework allows effective access and management of educational data at universities, and the 2PC technique guarantees transactions consistency at distributed databases. As a result, with the help of these mechanisms, the framework provides a scalable and reliable solution to the problem of automatic academic credit transfer in the large-scale MOOCs environment with a high validation precision, low latency and high consistency level.

2. Literature Review

However, while the development of Massive Open Online Courses (MOOCs) has facilitated the availability of higher education through allowing people all over the world to enrol in courses from various institutions, proper systems of collaboration and credit transfer among institutions are still insufficient. Indeed, initial studies underlined the significance of collaboration within MOOCs and the necessity of developing frameworks for the process [1]. An analysis of leading MOOC platforms uncovered problems in terms of interactivity, collaboration, and integration with institutions, thus pointing at the fact that MOOC systems are mostly oriented at content provision and not at credit mobility and academic interoperability [2]. Moreover, an examination of features of MOOC platforms showed that even though discussion forums and social networking tools help in fostering interactions, credit validation and transfer systems have not been developed yet [3].

A number of approaches have been implemented to support collaboration in online learning environments. Collaborative cloud-based systems have improved the process of communication, teamwork, and resources exchange between learners; however, this solution is limited to individual educational institutions and cannot be used for solving the issue of credit recognition across different institutions [4]. The literature review of institutional collaboration in MOOCs indicates that one of the key obstacles in terms of collaboration on the academic level is the absence of standard credit transfer system [5]. Moreover, researches in the field of MOOC effectiveness, retention, personalization, and predictive modeling of students' performance emphasize the importance of interoperability of educational infrastructure as an essential requirement for managing learner mobility and recognition of their achievements within different educational institutions [10] [11] [12] [13].

From the point of view of networking, the Border Gateway Protocol (BGP) is highly effective in implementing the policy-based routing decision-making process in autonomous systems of large-scale distributed systems. Work regarding autonomous system relationships has laid a basis for understanding policy-aware routing and distributed decision-making [6] [7]. There has also been some work on BGP configuration verification with the use of formal methods and model checking [9]. BGP performance analyses have shown the suitability of this protocol for large-scale communication [16].

Another field of interest has been formal verification methods, which have become increasingly popular in distributed systems. Mathematical formalisms based on automata theory have been proven to be efficient when used to study system behavior in terms of failures and policy restrictions; the mathematical proof of system correctness was provided as a result of the work [8]. The development in the area of threshold automata and formal verification methods proves the efficiency of automata theory-based verification methods as tools for proving correctness and consistency in distributed algorithms [14].

Several recent works have been done to consider blockchain technology as a possible means to solve the problem of managing and verifying academic credentials. The blockchain-enabled education system provides such advantages as transparency, immutability, and decentralization, but it usually encounters the issues of scalability, computing costs, interoperability, and technical complexity [15]. Thus, there is still a need for other distributed architectures that could provide secure and compliant credit transfers.

2.1 Research Gap

In spite of rapid development of MOOCs and e-learning platforms, credit transfer from one institution to another in an automated way is still a very problematic task. In the existing systems there is little possibility of automated credit transfer, since they mostly concentrate on content dissemination and engagement of learners, rather than automated credit recognition and policy enforcement [1]–[5]. In today's credit transfer process there is much manual evaluation and central management involved, which makes the process inefficient and inconsistent. Although BGP-based routing was found useful for policy-aware path selection in communication networks [6], [7], BGP has never been considered in academic credit transfer context. Similarly, automata-based verification methods were used in network validation [8], [9], [14] but never applied to validating academic policies and requirements. Blockchain-driven approaches provide a decentralized model but come with problems of high latency and difficulty of implementation [15]. In this regard, there is an important research gap to fill when it comes to implementing a solution for policy-aware routing, policy validation, coordination of distributed databases, and transaction consistency into one credit transfer model. To the best of our knowledge, none of the existing works incorporates routing in the spirit of BGP routing, DFA-driven validation, JDBC databases, and Two-Phase Commit coordination in an automated credit transfer system for universities.

3. Methodology

3.1 System Architecture

The proposed model creates a decentralized credit transfer network for universities, where universities function as autonomous entities but at the same time belong to a collaborative system of credit recognition. As shown in Figure 1, every university keeps its own academic record, transfer policy and validation process, but at the same time exchanges transfer information using policy-aware routing protocol. This architecture includes four main components: route selection based on BGP, policy validation based on DFA, distributed databases, and transaction coordination. With any initiation of credit transfer, the transfer path is selected, transfer policy is validated, and transfer decision is coordinated.

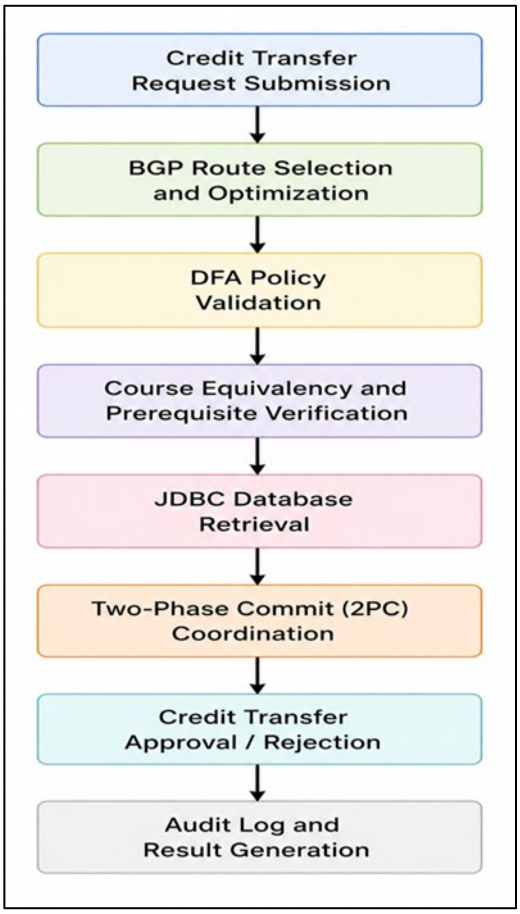

Figure 1. Proposed BGP-DFA credit transfer framework

3.2 BGP-based Routing for Credit Transfer

The proposed system architecture uses a routing technique based on BGP to establish the appropriate transfer paths among the collaborating institutions. Institutions will be treated as ASs and advertising their academic transfer information through special routing attributes such as course equivalency, policy compliance, and credit requirements. While discovering routes, candidate routes will be considered based on their policy compliance and academic fit. All routes that do not comply with the institution's requirements will be filtered out prior to optimization process to consider only feasible transfer routes.

Route Optimization Function

$$\Omega(r) = w_1 \cdot ES(r) - w_2 \cdot |AP(r)| + w_3 \cdot CW(r) \quad (1)$$

where,

- $ES(r) \in [0,1]$: denotes the normalized equivalency score
- $|AP(r)|$: denotes the number of hops in the ASPATH
- $CW(r) \in [1,5]$: is the rating for institutional reputation on a five-point scale
- $w_1, w_2, w_3 \in [0,1]$: are the weights assigned through parameters accordingly

Algorithm 1: Route selection and optimization

Input: Set of available routes R = $\{r_1, r_2, \ldots, r_n\}$ to destination university

Output: Optimal route r* satisfying policy constraints

Step 1: for each route r_i in R do

Step 2: if POLICY_COMP (r_i) = 0 then

Step 3: discard r_i // Route violates institutional policy

Step 4: end if

Step 5: end for

Step 6: R′ ← routes with POLICY_COMP = 1

Step 7: if |R′| = 0 then

Step 8: return NULL // No policy-compliant route exists

Step 9: end if

Step 10: r* ← argmax (r ∈ R′)
[w_1·EQUIV_SCORE(r) − w_2·|ASPATH(r)| + w_3·CRED_WEIGHT(r)]

Step 11: return r*

3.3 Deterministic Finite Automata for Policy Validation

Following the route selection, the request is validated through a Deterministic Finite Automata (DFA) driven validation procedure. Policy rules defined within the institution are converted into valid rules which can be evaluated via deterministic state transitions. The validation process looks into the prerequisites, course equivalency conditions, accreditation requirements, and institutional rules. This model enables us to validate our policy rules via finite-state transitions. The whole validation procedure is explained in Algorithm 2

$$(DFA)M = (Q, \Sigma, \delta, q_0, F) \tag{2}$$

where,

- Q : is a set of states that is not infinite, but the number of states indicates the validation stages
- Σ : is the input alphabet consisting of the policy rules and the course attributes
- δ : is the state transition function defined on $Q \times \Sigma \rightarrow Q$
- q_0 : is an element of Q that marks the initial state
- F : is a subset of Q that includes the accepting states (i.e., the policy is satisfied).

The protocol consists of two sequential phases: Prepare Phase and Commit Phase. During execution, the destination university acts as the coordinator, while the source university and intermediate validating institutions function as participants.

Algorithm 2: Multi-stage DFA validation engine

Input: Credit Transfer Request CTR, Institutional DFA M = $(Q, \Sigma, \delta, q\_0, F)$

Output: Boolean indicating policy compliance

Step 1: q ← q_0 //Initialize to start state

Step 2: tokens ← Lexical Analysis (CTR)

Step 3: Parse Tree ← Syntax Parser(tokens)

Step 4: for each rule σ ∈ Parse Tree do

Step 5: q ← δ (q, σ)

Step 6: if q = ERROR_STATE then

Step 7: return FALSE //Policy violation detected

Step 8: end if

Step 9: end for

Step 10: if q ∈ F then

Step 11: return TRUE //Request accepted

Step 12: else

Step 13: return FALSE //Incomplete policy satisfaction

Step 14: end if

Phase 1: Lexical Analysis

During the Phase 1 (Prepare Phase), the coordinator sends a PREPARE message to all participating universities. When the request comes in, every university independently assesses the request for transfer according to its internal academic criteria, accreditation standards, and student records. If all the conditions for transfer have been satisfied by the transfer, then the participant sends a YES response; otherwise, a NO response is sent.

Phase 2: Syntax Parsing

In the second phase (commit phase), the coordinator makes the decision by taking into consideration the votes he receives. If all participants give a YES vote, then the coordinator will broadcast a commit message and the entry of the transfer will be permanently committed in all the involved databases. On the other hand, if at least one participant gives a NO vote, or does not reply after the timeout period, the coordinator sends out an ABORT message; hence all transactions are terminated. Thus, this ensures the property of atomicity where either all the institutions accept the transfer or none accepts it (3).

$$G = (N, T, P, S) \tag{3}$$

where:

- N = {Policy, Condition, Expression}: Non-terminals
- T = {AND, OR, NOT, COURSE, GRADE}: Terminals
- P: Production rules
- S = Policy: Start symbol

Phase 3: Semantic Validation

The Two-Phase Commit protocol is an effective consensus protocol for distributed academic credits transfer network systems. The protocol makes sure that coordinated decision making occurs between independent universities, thus ensuring data consistency and integrity, and that approved transfers conform to the policies of all the institutions involved (4).

$$\delta(q,\sigma) = \left\{ \begin{matrix} q_1 \; if \; \sigma = PREREQ_{MET}, q_2 \; if \; \sigma = EQUIV_{SATISFIED}, q_3 \; if \; \sigma \\ = CREDIT_{WITHIN_{LIMIT}}, q_{\text{error}} \; otherwise \end{matrix} \right\} \quad (4)$$

3.4 Distributed Database Integration and Transaction Coordination

The framework incorporates distributed academic databases using JDBC-based communication facilities. Each institution involved in this framework keeps its own local repository for storing student records, course details, transfer policies, and transaction details. The academic information needed is obtained from the databases of respective institutions and made available to the validator during the transfer process. This process is illustrated by Algorithm 3.

Algorithm 3: Distributed query processing

Input: Student s, Credit transfer request CTR

Output: Validation result with supporting evidence

Step 1: src_{conn} ← JDBC.connect(u_{src} . $database_{url}$)

Step 2: $dest_{conn}$ ← JDBC. connect (u_{dest} . $database_{url}$)

Step 3: ▹ Retrieve student transcript from source university

// Retrieve student transcript from source

Step5: transcript←src_{conn} .execute

("SELECT*FROM Enrollments WHERE $student_{id}$ = "' + s.id + "'")

Step 6: policies ←$dest_{conn}$.execute

("SELECT * FROM Policies WHERE university_id = "' + u_dest.id + "'")

// Fetch destination policies

Step 8: policies ← $dest_{conn}$. execute

("SELECT * FROM Policies WHERE $university_{id}$ = "' + u_{dest}.id + "'")

Step 9: ▹ Execute policy validation // Convert policies to DFA

Step 10: M ← $DFA_{Parser}(policies.dfa_{representation})$ // Run validation

Step 11: result ← $DFA_{Validate}$ (CTR, M, transcript) // Log validation decision

Step 12: $dest_{conn}$. execute
("INSERT INTO $Transfer_{Requests}$ VALUES (..., result, ...)")

Step 13: return result

In order to provide consistency across many universities, a Two-Phase Commit (2PC) procedure is used. The coordinator gathers replies for validation from the participating universities and commits to the transaction only if all the universities agree on the request for transfer. The process of reaching consensus is depicted in Algorithm 4.

Algorithm 4: Two-phase commit for credit transfer

Input: Credit transfer request CTR, Path $P = [u_1, u_2, \ldots., u_k]$

Output: COMMIT or ABORT decision

Step 1: coordinator ← u_{dest}

Step 2: for each university u_i in P do

Step 3: vote[i] ← u_i . $validate_{local}$ (CTR)

Step 4: end for

Step 5: if all(vote) == TRUE then

Step 6: decision ← COMMIT

Step 7: else

Step 8: decision ← ABORT

Step 9: end if

Step 10: for each university u_i in P do

Step 11: if decision == COMMIT then

Step 12: u_i . $update_{database}$(CTR, status='approved')

Step 13: else

Step 14: u_i . rollback (CTR)

Step 15: end if

Step 16: end for

Step 17: return decision

3.5 Implementation Environment

An implementation of the framework was created as a part of the test to estimate automated transfer of credits in a decentralized environment. It combines a BGP-based route selection mechanism, a DFA-based policy validation process, a distributed database control system, and a transaction control system in one architectural structure. The test configuration was set up to simulate a federation of connected universities, where each university kept its own records of academic achievements and transfer policies. Students' transcripts, equivalent courses, accreditation policies, and transfer requests were used for testing different cases and system behavior under different policies and network configurations. The technology of implementation is listed in Table 1.

Table 1. Implementation environment and technology configuration

Component	Technology
Application Framework	Java, Spring Boot
Routing Engine	FR Routing (FRR)
Policy Validation	ANTLR4-based DFA
Database	MySQL 8.0
Database Connectivity	JDBC
Transaction Coordination	Two-Phase Commit (2PC)
Experimental Environment	100 University Nodes

4. Results and Discussion

The BGP-DFA framework was tested via experiments that aimed to simulate various inter-university credit transfer processes, with different networks and complexity of policies. The testing environment involved 100 virtual university nodes operating in a distributed manner, wherein each institution had its own database that included students' information, courses offered by them, and transfer rules. BGP routing was configured according to the academic routing attributes, and institutions' policies were modeled and verified based on the DFA verification engine. Performance was assessed in terms of route selection efficiency, policy validation accuracy, latency, throughput, and distributed transaction consistency.

4.1 Route Selection Performance

The performance of the route selection technique using BGP is shown in Figure 2 under different routing scenarios. It can be noted that the trend shows that the proposed route selection algorithm successfully weeds out the transfer paths which do not meet the policy before optimizing routes, thus decreasing the evaluation of unnecessary paths. The steady increase in processing overhead confirms the scalability of the routing technique as the number of candidate institutions increases.

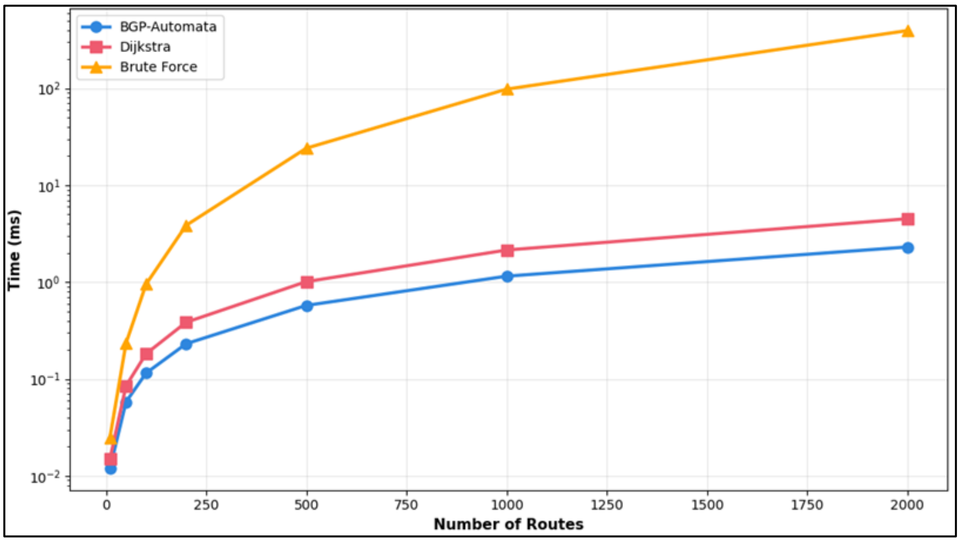

Figure 2. Scalability analysis of BGP-based route selection under increasing routing complexity

4.2 DFA Policy Validation Performance

The performance of the DFA-based policy verification engine for validation is shown in Figure 3. The findings indicate that the formal validation approach is able to preserve decision-making capability even as the complexity of the institution's policies increases. The deterministic nature of the state transition approach ensures consistency of evaluation of the conditions of pre-requisite requirements, accreditation, and equivalencies without any form of ambiguity in the execution of the policies.

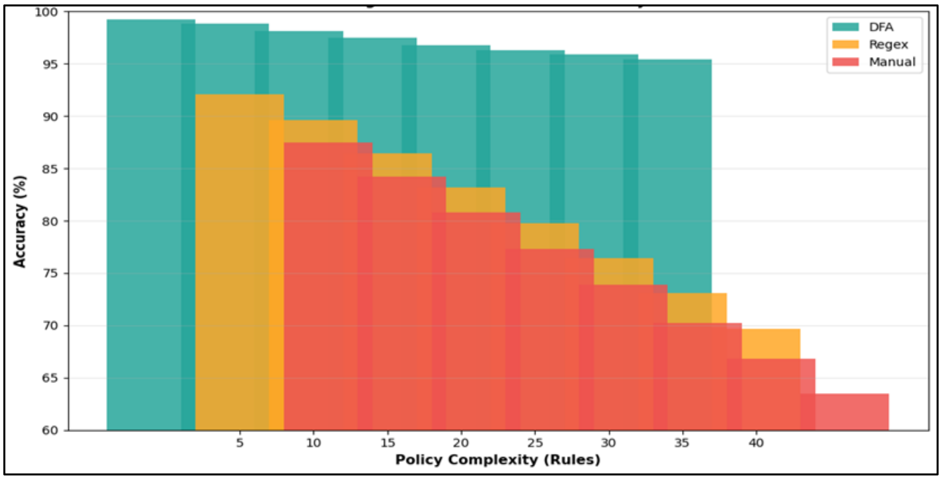

Figure 3. Policy validation reliability of the DFA-based verification engine

4.3 System Latency Analysis

The figure 4 shows the response latency in relation to distributed credit transfer processing. From the findings above, it is clear that the architecture is capable of ensuring constant response behavior regardless of the number of institutions taking part in the process. Decentralized route discovery together with local policy verification and effective database interactions ensures reduced communication cost during the transfer process.

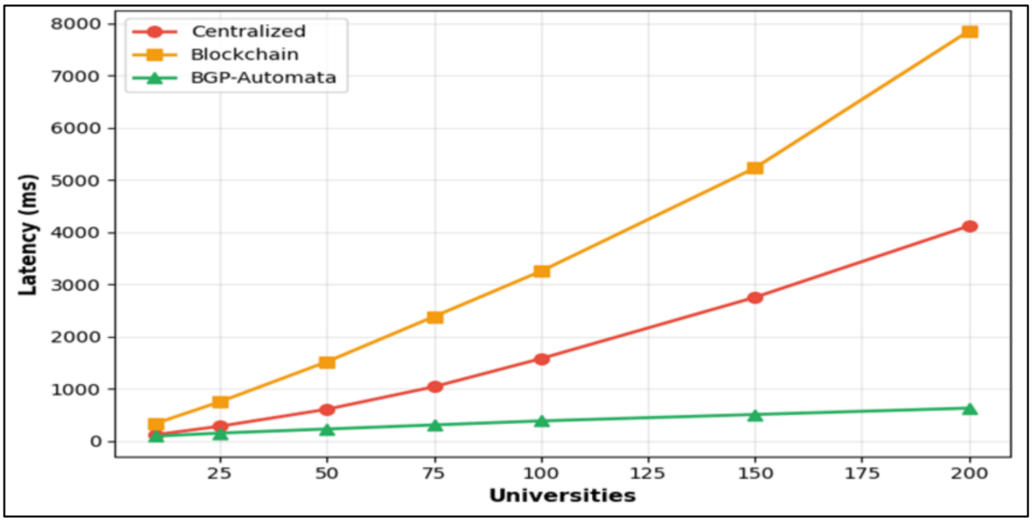

Figure 4. Response latency performance during distributed credit transfer processing

4.4 Throughput Analysis

Throughput features of the proposed model are presented in Figure 5. The model proved capable of maintaining its request-processing efficiency under growing workload. Effective utilization of resources in distributed organizational nodes was achieved through implementation of route optimization, policy validation, and transaction management techniques. As a result, processing of multiple transfer requests can occur simultaneously without any significant decrease in performance of the system. This feature is particularly critical for the large-scale academic networks.

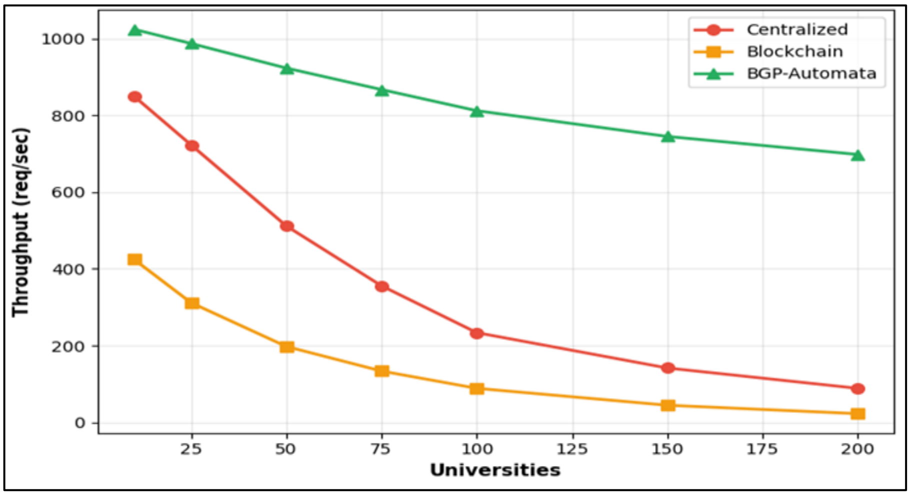

Figure 5. Throughput analysis of the proposed distributed credit transfer framework

4.5 Distributed Transaction Consistency

Distributed validation was also examined via the large-scale transfer transactions among many participating institutions. Two-Phase Commit algorithm provided for the consistency of decision making among the distributed databases and avoided inconsistency of updates in the transfers in course of transaction execution. Also, database communication using JDBC allowed for efficient acquisition and handling of student data during the process of validation.

4.6 Overall Performance Evaluation

The performance of the proposed BGP-DFA credit transfer framework is presented in Table 2. It can be seen from the results that incorporation of policy-aware routing, policy validation using DFA, and distributed transactions is able to provide effective processing of credit transfers with high reliability and scalability. The framework demonstrated high levels of reliability of validation and transaction consistency while ensuring efficient processing of requests from a large number of organizations.

Table 2. Overall performance of the proposed BGP-DFA framework

Performance Metric	Value
Validation Accuracy	96.3%
Transaction Consistency	99.7%
Average Query Latency	23.4 ms
Throughput	812 req/s
Supported Institutions	> 200

5. Conclusion

The research work has described the DFA-based Policy Validation in BGP-Routed Credit Transfer Networks framework that can automate the academic credit transfer between different universities. The combination of BGP-based policy aware routing technique along with DFA-based formal verification provides the basis for the framework allowing the automation of the process, preserving the autonomy of each educational institution. JDBC-SQL integration and Two-Phase Commit protocol guarantee consistency and coordination of transactions between involved universities. The experimental analysis showed high validation accuracy, low latency, transaction consistency and increased throughput in comparison with conventional centralized and blockchain-based solutions. Thus, the paper has shown the possibility of using the principles of networking, formal verification and distributed databases for the automation of the credit transfer between universities. In the future, this research can be extended to explore the usage of the framework for real university environments, the application of machine learning techniques for predicting course equivalencies, privacy preserving authentication, the use of hybrid blockchain, policy learning, cross-border accreditation standards and cloud native architectures.

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