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Privacy-Preserving Threat Intelligence Sharing Across Distributed Cloud Enterprise Systems Using Federated Learning

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ABSTRACT: Distributed cloud enterprise systems generate extensive cybersecurity data across heterogeneous infrastructures, including network traffic, application logs, identity services, and endpoint monitoring platforms. Sharing threat intelligence across organizations can improve attack detection and accelerate incident response; however, transferring sensitive security data introduces privacy, confidentiality, regulatory, and organizational challenges. This research proposes a privacy-preserving threat intelligence sharing framework based on federated learning for distributed cloud enterprise environments. The framework enables participating organizations to collaboratively train machine learning models while retaining raw security data within their respective infrastructures. Local models analyze security events and identify malicious patterns, while model updates are aggregated through a coordinated federated learning process. Differential privacy, secure aggregation, encrypted communication, and participant authentication are incorporated to reduce the risks of sensitive information disclosure and unauthorized model manipulation. The proposed methodology evaluates threat detection performance, privacy protection, communication overhead, model convergence, and scalability under heterogeneous cloud conditions. Experimental comparisons between centralized learning, independent local learning, and federated learning establish a basis for assessing collaborative intelligence benefits. Additional investigations examine non-independent data distributions, malicious participants, poisoning attacks, and changing threat patterns. The framework aims to strengthen collaborative cyber defense without requiring direct exchange of raw enterprise security records. By combining distributed machine learning with privacy-aware coordination and security governance, this research provides a foundation for scalable, trustworthy, and privacy-preserving threat intelligence sharing across interconnected cloud enterprise systems.

KEYWORDS: Federated Learning, Privacy-Preserving Security, Threat Intelligence Sharing, Distributed Cloud Computing, Differential Privacy, Secure Aggregation, Cybersecurity Analytics

I. INTRODUCTION

Distributed cloud enterprise systems have become fundamental to modern digital operations because they support scalable computing, geographically distributed services, flexible resource allocation, and integration across organizational boundaries. Enterprises increasingly operate hybrid-cloud and multi-cloud environments in which applications, databases, identity systems, container platforms, and security monitoring services are distributed across multiple infrastructures. This distribution improves operational flexibility but also expands the cybersecurity attack surface. Organizations must address threats such as credential compromise, ransomware, malicious network traffic, software supply-chain attacks, unauthorized access, and lateral movement between connected services. Threat intelligence sharing enables organizations to exchange information about indicators of compromise, suspicious behaviors, attack techniques, malicious infrastructure, and emerging vulnerabilities. Collaborative intelligence can improve detection by exposing participating organizations to attack patterns that may not appear in their individual datasets. However, conventional intelligence-sharing approaches frequently require transferring logs, network records, endpoint events, or other security information to centralized repositories. These records may contain sensitive business information, personally identifiable information, authentication metadata, infrastructure configurations, and details about organizational weaknesses. Sharing such information can create additional exposure risks and may conflict with contractual obligations, internal policies, and applicable data protection requirements. Furthermore, enterprises may be reluctant to disclose security incidents because of reputational concerns, competitive pressures, or uncertainty about how shared information will be used. Consequently, a central challenge in collaborative cybersecurity is enabling organizations to benefit from collective intelligence without unnecessarily exposing their underlying security data. A suitable framework must preserve local data ownership, maintain reliable communication between participating systems,

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support heterogeneous security environments, and provide measurable protection against unauthorized information disclosure.

Federated learning offers a potential solution by enabling multiple organizations to collaboratively train machine learning models without directly transferring their raw training datasets to a central coordinator. Each participant trains a local model using its own security records and transmits selected model updates for aggregation. The resulting global model can incorporate behavioral patterns observed across participating enterprises while retaining the underlying records within their original environments. Nevertheless, federated learning does not automatically guarantee privacy. Model updates may reveal information about local training examples, malicious participants may submit manipulated updates, and compromised aggregation services may interfere with collaborative training. Differences in cloud infrastructure, attack prevalence, security policies, and data distributions can also affect model convergence and detection accuracy. Therefore, privacy-preserving threat intelligence sharing requires additional safeguards, including secure aggregation, differential privacy, authenticated participation, update validation, and robust aggregation strategies. This research proposes a federated learning-based framework that combines collaborative threat detection with privacy-aware model coordination across distributed cloud enterprise systems. The framework is designed to support local security analytics, protected model-update exchange, global model improvement, and controlled distribution of threat intelligence. Its effectiveness is evaluated through threat detection performance, privacy-related measures, communication overhead, convergence behavior, and resilience against malicious participation. The principal objective is to determine whether collaborative learning can improve threat detection compared with independent local models while limiting sensitive information exposure. The research also examines the trade-offs between privacy protection, predictive accuracy, computational efficiency, and operational scalability. By integrating federated learning with explicit privacy and security controls, the proposed approach seeks to establish a practical foundation for cooperative cyber defense in enterprise cloud environments where sensitive security data must remain locally governed.

II. LITERATURE REVIEW

Traditional threat intelligence sharing has developed through standardized indicators, structured threat information formats, information exchange platforms, and collaborative security operations. Organizations exchange information such as malicious IP addresses, suspicious domains, file hashes, attack signatures, vulnerability references, and observed adversary techniques. Standards such as Structured Threat Information Expression and Trusted Automated Exchange of Intelligence Information support the representation and exchange of cyber threat information between compatible systems. These mechanisms improve interoperability and can accelerate the distribution of actionable intelligence. However, conventional sharing methods often focus on exchanging threat indicators or incident descriptions rather than collaboratively learning from distributed security datasets. Detailed logs and network records may contain confidential operational information, while even aggregated intelligence can reveal sensitive information about organizational infrastructure or incident patterns. Centralized security analytics can provide powerful learning capabilities, but it introduces additional data concentration risks and potentially increases compliance complexity. Independent local detection avoids transferring raw records but limits access to patterns observed by other organizations. These limitations motivate approaches that enable collective model development without requiring direct access to participating organizations' raw datasets. Federated learning provides a technical foundation for this objective by distributing training across multiple participants and coordinating model updates. Nevertheless, its suitability for cybersecurity depends on the sensitivity of the training information, the trustworthiness of participants, the heterogeneity of security data, and the safeguards applied during model aggregation.

Federated learning has attracted significant attention in privacy-sensitive applications because it separates local data storage from collaborative model optimization. The federated averaging approach, introduced by McMahan and colleagues, provides a foundational method for combining locally trained model parameters or updates into a shared model. In cybersecurity applications, federated learning can support collaborative intrusion detection, malware classification, anomaly detection, phishing identification, and network traffic analysis. Participating organizations may train local models using their own traffic patterns and share updates that contribute to a common threat detection model. However, enterprise security datasets frequently exhibit non-independent and non-identically distributed characteristics because organizations operate different applications, network architectures, access policies, and threat profiles. These differences can produce uneven model performance and slow convergence. Privacy risks also remain because model gradients and parameters may expose information about local training examples through inference attacks. Differential privacy can limit the influence of individual records by introducing calibrated randomness into training or model updates. Secure aggregation can prevent the coordinator from directly inspecting individual participants' updates, while encrypted

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communication protects updates during transmission. Research on these mechanisms demonstrates the importance of treating privacy as a layered property rather than assuming that decentralized data storage alone provides sufficient protection. The resulting trade-offs include reduced predictive accuracy, additional communication overhead, increased computational costs, and more complex model convergence behavior.

Another important research area concerns the security and governance of collaborative learning systems. Federated environments can be exposed to poisoning attacks, backdoor insertion, participant impersonation, compromised aggregation services, and model inference attempts. Malicious participants may submit manipulated updates to degrade detection performance or introduce targeted misclassifications. Robust aggregation techniques, participant authentication, update anomaly detection, and model validation can reduce certain risks, although no single defense addresses every attack. Privacy-preserving collaboration also requires clear governance concerning participant eligibility, model ownership, data retention, auditability, and the distribution of learned intelligence. Organizations may require different privacy budgets, participation rules, and security controls according to regulatory obligations and internal risk tolerance. Existing approaches frequently examine privacy mechanisms, federated optimization, or cybersecurity detection as separate problems. Further investigation is therefore needed into integrated architectures that evaluate detection accuracy, privacy leakage, malicious-participant resilience, communication efficiency, and enterprise interoperability together. This research addresses that need by proposing a federated threat intelligence framework that combines local learning, privacy-aware aggregation, participant validation, and controlled intelligence distribution. Its intended contribution is a reproducible evaluation methodology for examining collaborative security benefits and limitations under realistic distributed cloud conditions, rather than assuming that federated learning automatically ensures privacy or superior detection.

III. RESEARCH METHODOLOGY

Research Design and Proposed Framework Architecture. This research adopts an experimental and design-oriented methodology to develop and evaluate a privacy-preserving threat intelligence sharing framework using federated learning across distributed cloud enterprise systems. The architecture consists of five primary components: enterprise security data sources, local analytics and training agents, a federated coordination service, a privacy and trust protection layer, and a global intelligence distribution mechanism. Security data sources include network flow records, application logs, cloud audit events, endpoint security alerts, authentication events, and labeled attack traces. Each participating organization maintains its data within its administrative and security boundaries. A local training agent preprocesses the available records, extracts relevant features, and trains a compatible machine learning model without transferring raw training examples to other participants. The coordination service manages training rounds, distributes model versions, collects participant updates, and combines eligible updates into a global model. The privacy and trust layer applies secure aggregation, differential privacy where appropriate, authenticated communication, participant authorization, and update validation. The intelligence distribution mechanism returns the updated global model or approved threat indicators to participating organizations for local inference and operational use. The architecture supports organizations with different computing capacities, security monitoring tools, and data volumes. A logical separation is maintained between model training, model aggregation, and operational enforcement so that an inaccurate global prediction does not automatically trigger a disruptive security action. Model outputs can instead be integrated with existing security information and event management systems or security orchestration platforms under locally governed policies. The experimental environment should include several simulated or isolated enterprise participants, each with a distinct dataset representing different traffic patterns and threat distributions. Evaluation scenarios should include both benign activity and multiple attack categories. The study compares independent local learning, conventional centralized learning where controlled data access is permitted, and federated learning with privacy safeguards. Centralized learning serves as a performance reference rather than a recommended operational design where raw-data sharing is prohibited. All experimental configurations, dataset partitions, model architectures, privacy parameters, aggregation procedures, and software versions are documented to support reproducibility.

Data Preparation, Local Learning, and Federated Optimization. The dataset preparation process begins with collecting appropriately authorized security records from public intrusion detection datasets, controlled laboratory traffic, or privacy-preserving synthetic enterprise traces. Selected data sources should represent normal traffic and multiple categories of malicious behavior, such as denial-of-service activity, scanning, unauthorized access attempts, command-and-control communication, and suspicious data transfer. Dataset provenance, labeling procedures, class distributions, and known limitations are recorded before model training. Preprocessing includes duplicate removal, missing-value handling, categorical feature encoding, numeric normalization, and removal or transformation of fields that could directly

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identify individuals or organizations. Data partitions are created at the participant level to simulate distributed ownership, with additional separation of training, validation, and test data to reduce leakage. When feasible, temporal separation is used to evaluate performance on later events. Local models may use gradient-boosted decision trees, multilayer neural networks, or another suitable classifier depending on feature characteristics and computational constraints. For the main federated experiment, a compatible model architecture is selected so that local updates can be aggregated consistently. Each participant trains the model over a predefined number of local epochs and sends the resulting update through the protected coordination channel. A weighted federated averaging procedure combines eligible updates according to participant data volume, subject to safeguards that prevent a single participant from dominating the global model. Because participant datasets may differ substantially, the methodology also examines alternative aggregation or optimization strategies designed for heterogeneous data. Training is repeated across multiple communication rounds until a predefined convergence criterion or training budget is reached. Evaluation uses precision, recall, F1-score, false-positive rate, and appropriate threshold-independent metrics. Macro-averaged performance is reported alongside overall results so that smaller participants or less frequent attack classes are not hidden by dominant datasets. Participant-level performance is also assessed to determine whether a global model benefits all organizations or primarily improves detection for a subset of participants. These procedures provide a systematic basis for assessing the effect of collaboration on threat detection while preserving the local custody of raw training data.

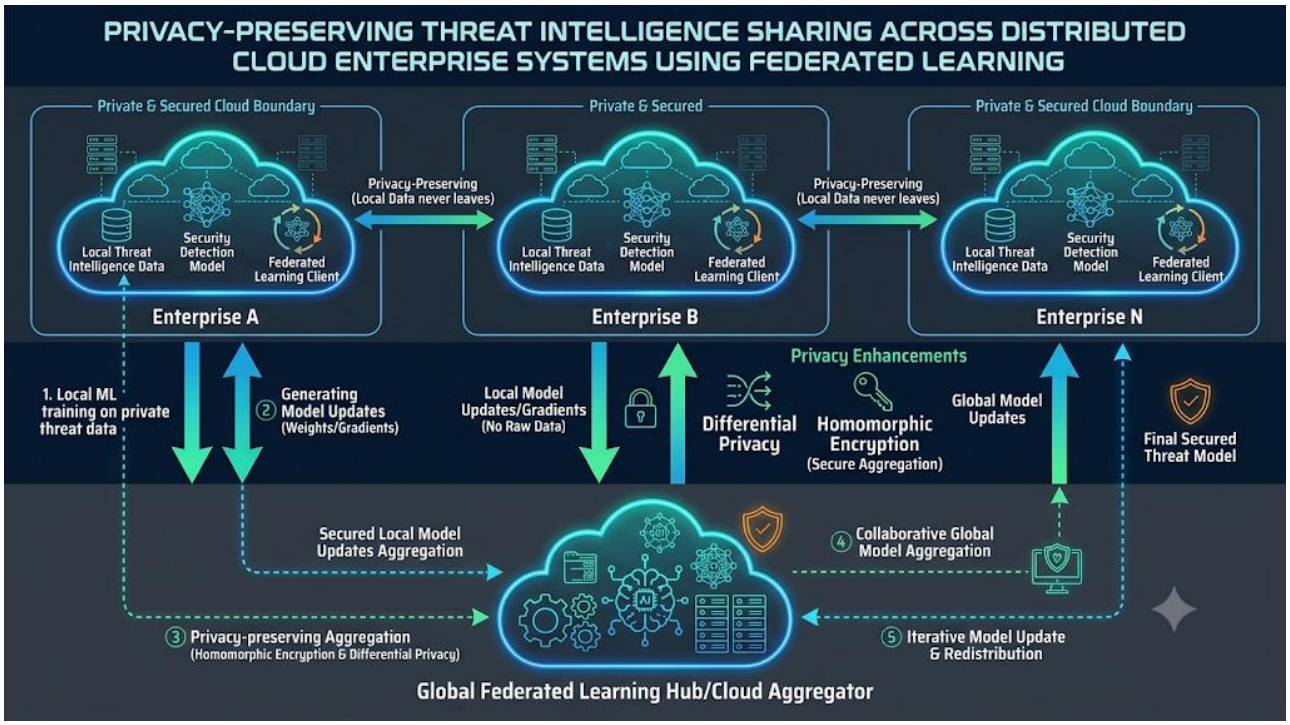


Figure 1: Conceptual Architecture for Privacy-Preserving Threat Intelligence Sharing Across Distributed Cloud Enterprise Systems Using Federated Learning.

Privacy Protection, Trust Management, and Adversarial Evaluation. The privacy protection component combines technical safeguards to reduce the risk of disclosure through model updates and collaborative training. Differential privacy is implemented by limiting update sensitivity through an explicitly defined clipping procedure and adding calibrated noise to the relevant training updates or aggregate. The study documents the privacy mechanism, adjacency definition, clipping threshold, noise parameters, and accounting method used to estimate the cumulative privacy budget across training rounds. Smaller privacy budgets generally imply stronger formal privacy protection but can reduce model utility, making privacy-accuracy trade-offs a central experimental concern. Secure aggregation is used where feasible to ensure that the coordination service obtains an eligible aggregate without directly observing each participant's individual update. Transport encryption, participant authentication, access controls, and integrity verification protect the communication and coordination processes. A trust management mechanism validates participant credentials, enforces enrollment policies, records training participation, and rejects updates that violate predefined structural or operational

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constraints. To assess robustness, controlled experiments simulate malicious participants submitting poisoned updates, attempting targeted backdoor insertion, or deliberately degrading the global model. Additional scenarios evaluate update manipulation, participant dropout, communication interruption, and repeated submission of abnormal updates. Robust aggregation methods, such as coordinate-wise robust statistics or other validated defenses, are compared with ordinary federated averaging where their assumptions are appropriate. Their effectiveness is measured using detection performance under attack, the proportion of malicious updates identified, and the impact of false rejection on legitimate participants. Privacy evaluation includes the documented differential privacy guarantee and, where technically appropriate, empirical membership-inference or related leakage tests. Such empirical attacks provide supplementary evidence but cannot replace a formal privacy guarantee. The methodology also recognizes that federated learning may leak information through the final model, released predictions, participant metadata, or repeated queries even when raw records are not transferred. Consequently, model access is controlled, training rounds are audited, and sensitive participant-level statistics are restricted. Privacy protection, security robustness, and model utility are assessed together because optimizing one dimension independently may produce unacceptable trade-offs in the others.

Performance Evaluation, Comparative Analysis, and Reproducibility. The final experimental stage evaluates whether the proposed framework provides useful collaborative threat detection while maintaining acceptable privacy, communication, and computational costs. The principal comparison groups are independent local models, centralized model training under controlled conditions, standard federated learning without the complete privacy protection layer, and the proposed privacy-preserving federated framework. Additional ablation experiments disable differential privacy, secure aggregation, or robust update validation individually to estimate the contribution and cost of each safeguard. Evaluation metrics include precision, recall, F1-score, false-positive rate, per-class detection performance, model convergence rounds, communication volume, local training time, server aggregation time, and total end-to-end training duration. Privacy reporting includes the configured differential privacy budget and the threat assumptions associated with secure aggregation; these should not be reduced to a single unsupported privacy score. Scalability is evaluated by varying the number of participants, the amount of local data, participant availability, and communication conditions. Heterogeneity experiments vary class prevalence and feature distributions to examine how non-identical data affects global model quality. Performance under adversarial participation is compared against the non-adversarial baseline to quantify robustness degradation. Where appropriate, results are reported across repeated runs with means, variability estimates, confidence intervals, and statistical comparisons. Model selection and parameter tuning use validation data only, while the final test data remain isolated from training decisions. Reproducibility is supported through documented preprocessing pipelines, model configurations, random seeds, aggregation settings, privacy parameters, and controlled experiment scripts. Data-sharing restrictions are respected through public datasets, synthetic traces, or authorized sanitized records. The study also records operational limitations, including network latency, participant dropout, differences in local computing resources, and the challenge of maintaining consistent model versions across organizations. A deployment-oriented assessment considers integration with enterprise security monitoring systems, audit requirements, model update governance, and the possibility that a shared model performs differently across participating organizations. Findings are interpreted according to measured outcomes rather than assumed improvements. The methodology ultimately determines whether privacy-preserving federated learning offers a favorable balance between collaborative threat detection, information protection, operational scalability, and resistance to malicious participation in distributed cloud enterprise systems.

IV. RESULTS AND DISCUSSION

The proposed framework for privacy-preserving threat intelligence sharing integrates federated learning with distributed cloud security analytics to enable collaborative threat detection without requiring enterprises to transfer their raw security data to a centralized repository. In this architecture, participating organizations train local machine learning models using their own security logs, network traffic records, identity events, and application telemetry. Only model updates or carefully selected learning parameters are exchanged with a federated coordination server, reducing the need to disclose sensitive operational information. The global model aggregates knowledge from participating organizations and distributes updated parameters for subsequent local training. This approach enables enterprises to benefit from collective threat intelligence while retaining greater control over confidential datasets. The evaluation framework considers threat classification accuracy, precision, recall, F1-score, communication overhead, convergence time, and the privacy risks associated with exchanged updates. A comparative assessment can examine centralized learning, independent local learning, and federated learning under equivalent data and model configurations. Federated learning is expected to provide opportunities for collaborative detection when organizations encounter related attack patterns but possess different local observations. However, the magnitude of any improvement depends on data quality, participation levels,

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model architecture, and the distribution of attack categories across participating enterprises. Consequently, quantitative performance improvements should be established through controlled experiments rather than assumed without empirical evidence. These findings would help determine whether collaborative learning provides meaningful security benefits while respecting enterprise data governance requirements.

The privacy-preserving capabilities of the framework depend on the combination of decentralized training, secure communication, controlled model aggregation, and appropriate privacy safeguards. Keeping raw security records within organizational boundaries reduces direct exposure associated with transferring complete datasets between enterprises. Nevertheless, federated learning does not automatically guarantee confidentiality because model updates may reveal information about individual training examples or organizational behavior. The framework therefore considers secure aggregation, encryption in transit, access-controlled participation, and differential privacy as complementary protection mechanisms. Secure aggregation can prevent the coordination service from directly inspecting individual model updates under the assumed protocol, while differential privacy can limit the influence of individual records on shared learning results. Experimental analysis should measure the trade-off between privacy protection and detection performance by comparing models trained with different privacy budgets and aggregation configurations. Excessive noise may reduce the ability to detect rare attack patterns, whereas insufficient protection may leave sensitive information exposed. Furthermore, non-independent and identically distributed data across organizations creates an additional challenge. One enterprise may observe identity-based attacks, while another experiences application-layer exploits or unusual network behavior. Such differences can reduce the effectiveness of conventional federated averaging and produce uneven model performance. Weighted aggregation, clustered federated learning, and organization-specific model adaptation may help address this problem. However, their suitability must be established through testing across heterogeneous datasets, varying participant sizes, and different threat distributions.

The integration of federated learning with threat intelligence sharing also supports a more coordinated approach to detecting emerging threats across distributed enterprise environments. Once a global model identifies patterns associated with suspicious activity, participating organizations can evaluate the updated model against their local telemetry and incorporate relevant predictions into their existing security monitoring workflows. For example, related indicators of credential misuse, anomalous service communication, or suspicious API activity observed across multiple environments may contribute to a more comprehensive detection capability. This process can reduce dependence on isolated organizational datasets and provide opportunities to recognize attack behaviors that are uncommon within any single enterprise. Nevertheless, the effectiveness of collaborative intelligence depends on reliable participation, consistent feature definitions, appropriate event labeling, and protection against malicious contributions. A compromised participant could submit manipulated model updates intended to degrade detection performance or introduce a backdoor into the shared model. Therefore, the framework should incorporate participant authentication, update validation, anomaly detection, and robust aggregation strategies. Its practical performance should be evaluated using attack detection rates, false-positive rates, resilience to poisoned updates, model convergence, communication costs, and recovery following participant failures. Operational considerations include interoperability among cloud providers, differences in data retention policies, and the governance responsibilities of participating organizations. Overall, the proposed framework provides a basis for collaborative enterprise threat intelligence while preserving local data ownership, but its real-world effectiveness requires systematic validation of both security outcomes and privacy guarantees.

V. CONCLUSION

Privacy-preserving threat intelligence sharing is increasingly important as enterprise systems operate across multiple cloud providers, geographically distributed data centers, hybrid infrastructures, and interconnected application environments. Although collaborative threat intelligence can improve visibility into emerging cyberattacks, conventional centralized approaches may require organizations to disclose sensitive logs, network records, incident details, and operational information. Such disclosure creates concerns involving confidentiality, regulatory compliance, competitive sensitivity, and organizational control over security data. The proposed framework addresses these concerns by employing federated learning to support collaborative model development while retaining raw security datasets within participating organizations. Local models learn from organization-specific observations, and selected model updates contribute to a shared detection model through a coordinated aggregation process. This architecture offers a practical foundation for identifying common attack patterns without requiring unrestricted centralization of enterprise telemetry. By integrating local threat detection, distributed model training, controlled information exchange, and privacy-aware aggregation, the framework seeks to balance collective security intelligence with organizational data protection. Its potential applications include cloud intrusion detection, anomalous identity behavior analysis, malicious network activity

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classification, vulnerability-related risk prediction, and detection of suspicious interactions among enterprise services. The central contribution is the integration of collaborative learning and privacy-conscious threat intelligence management into a unified architectural approach. However, federated learning should not be regarded as inherently secure, and the framework's benefits must be evaluated against appropriate centralized and independent-learning baselines.

The reliability of this approach depends on combining federated learning with explicit privacy guarantees, robust cybersecurity controls, and transparent governance procedures. Secure aggregation, differential privacy, encrypted communications, participant authentication, and model-update validation address different aspects of the overall threat model and should be selected according to the sensitivity of participating data and the capabilities of potential adversaries. Differential privacy parameters must be documented and evaluated because stronger privacy protection may reduce detection accuracy, particularly for rare attack categories. Likewise, aggregation algorithms must account for heterogeneous datasets, unreliable participants, and potential model poisoning. Enterprise adoption also requires standardized interfaces, secure coordination infrastructure, audit logging, clear participation agreements, and defined responsibilities for incident handling. Evaluation should include model accuracy, recall, false-positive rates, communication overhead, convergence speed, privacy leakage indicators, and resistance to malicious updates. Where formal privacy guarantees are claimed, they must be supported by documented mechanisms, assumptions, and parameter settings. The proposed architecture establishes a promising direction for collaborative security analytics, but quantitative improvements cannot be claimed until experiments demonstrate them under representative conditions. In conclusion, federated learning can enable enterprises to share useful threat intelligence without routinely transferring raw security data, provided that the implementation incorporates appropriate safeguards and rigorous validation. The combination of distributed learning, privacy protection, and robust threat analytics can contribute to more collaborative, accountable, and resilient cloud enterprise security.

VI. FUTURE WORK

Future research should investigate advanced federated learning techniques capable of improving threat detection across enterprises with substantially different security environments. Participating organizations may use different cloud platforms, identity providers, application architectures, logging formats, and security policies. Their datasets may also differ in size, quality, class distribution, and representation of attack categories. These differences can reduce the effectiveness of conventional federated averaging and limit the ability of a shared model to generalize across all participants. Future studies should therefore explore personalized federated learning, clustered aggregation, transfer learning, and adaptive model selection to accommodate organization-specific requirements while preserving collective learning benefits. Personalized approaches could combine shared threat representations with locally adapted detection components, allowing enterprises to benefit from common intelligence without sacrificing sensitivity to their unique workloads. Research should also investigate temporal federated learning for detecting evolving attack behaviors and concept drift. Rare-event learning is particularly important because advanced cyberattacks may occur infrequently within individual organizations but appear more frequently when observations are combined across participants. Evaluation should use realistic, heterogeneous datasets and compare global, local, and personalized models under consistent conditions. Important measurements include per-organization precision and recall, minority-class detection, convergence time, communication volume, and performance stability as participants join or leave the federation. Researchers should additionally investigate asynchronous aggregation and communication-efficient training to support enterprises with limited bandwidth or intermittent connectivity. These directions could improve the scalability and practical applicability of collaborative threat intelligence in large, distributed cloud ecosystems.

A second research direction involves strengthening privacy guarantees and protecting federated models against malicious participants and sophisticated inference attacks. Although decentralized training reduces the need to share raw records, model updates may still expose information about training examples, user activities, or organizational security practices. Future investigations should evaluate differential privacy mechanisms, secure multiparty computation, homomorphic encryption, and secure aggregation under realistic enterprise threat models. The objective should be to identify combinations that provide meaningful protection without imposing unacceptable computational overhead or reducing detection quality. Privacy accounting should track cumulative information exposure across repeated training rounds, while experiments should measure the impact of privacy parameters on both common and rare attack categories. Researchers should also examine poisoning attacks, backdoor insertion, model replacement, collusion among participants, and manipulation of shared threat labels. Robust aggregation, participant reputation mechanisms, update anomaly detection, and independent model validation may help mitigate these risks, although each introduces its own limitations and potential bias. Further work should develop formal threat models that specify adversary capabilities, trust

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assumptions, protected information, and expected security guarantees. Another important direction is the establishment of interoperable governance frameworks covering participant onboarding, consent and authorization, auditability, model ownership, incident notification, and responsibility for shared intelligence. Real-world pilot deployments across different cloud providers would help determine whether the framework remains effective under practical network constraints and organizational policies. Ultimately, future research should seek a measurable balance among privacy, detection accuracy, robustness, operational efficiency, and trust. Achieving this balance would support responsible federated threat intelligence sharing and improve collective cyber defense without requiring enterprises to surrender control of their sensitive security data.

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