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Formal Verification of Multi-Party Privacy Protocols Using Probabilistic Automata and Symbolic Abstraction in High-Stakes Data Environments

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Abstract

Ensuring data privacy in high-stakes, multi-party computation (MPC) environments demands formally verified protocols that accommodate uncertainty and adversarial behavior. This paper presents a formal verification framework for multi-party privacy protocols using probabilistic automata and symbolic abstraction. Probabilistic automata capture non-determinism inherent in real-world networked environments, while symbolic abstraction facilitates scalable verification of complex cryptographic operations. We validate our framework against representative healthcare and financial data-sharing scenarios, demonstrating soundness, scalability, and practical tractability. Our findings indicate improved verification efficiency and greater resilience to probabilistic inference attacks when compared with baseline non-symbolic models.

Keywords:

Formal Verification, Probabilistic Automata, Symbolic Abstraction, Multi-Party Computation, Privacy Protocols, High-Stakes Data, Secure Communication, Protocol Analysis.

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1. Introduction

Formal verification has emerged as a foundational technique in cryptographic protocol assurance, especially when applied to high-stakes domains such as healthcare, finance, and law enforcement. As multi-party computation (MPC) systems gain adoption, ensuring the privacy and correctness of such protocols becomes imperative. Traditional verification techniques often falter in probabilistic settings or when adversarial uncertainties dominate system behavior. This calls for robust models capable of capturing both probabilistic transitions and symbolic reasoning.

Probabilistic automata offer a compelling solution by encoding system behavior under uncertainty. However, the state explosion problem becomes acute as protocol complexity scales. To address this, symbolic abstraction techniques—particularly those leveraging SMT (Satisfiability Modulo Theories) solvers—have been proposed to compress large state spaces into abstract representations while preserving correctness guarantees. By integrating these two approaches, we aim to develop a scalable, rigorous verification framework tailored to high-stakes multi-party data-sharing protocols.

2. Literature Review

The intersection of probabilistic modeling and privacy protocol verification has seen extensive exploration. Notably, Baier and Katoen (2008) provided a foundational treatment of probabilistic model checking, formalizing Markov decision processes for use in security protocols. McLean (1994) proposed the concept of noninterference in security systems, which laid groundwork for compositional reasoning in privacy guarantees.

Kwiatkowska et al. (2011) introduced the PRISM model checker for probabilistic systems, widely used in security protocol verification. Backes et al. (2004) developed symbolic models for cryptographic verification using applied pi calculus, while Blanchet (2001) leveraged ProVerif to symbolically analyze protocol secrecy and authentication. These early methods, while effective for small systems, fail to scale under high-state or real-time constraints.

More recent work by Delaune and Kremer (2012) emphasizes the value of symbolic abstraction for large-scale verification. Similarly, Lowe (1996) formalized model checking approaches for protocols like Needham-Schroeder, highlighting the role of automated reasoning in adversarial settings. Despite these advances, few approaches have unified symbolic abstraction with probabilistic verification in the context of multi-party data privacy, a gap this paper addresses.

3. Methodology

3.1 System Architecture Overview

We design a formal verification pipeline comprising three stages: symbolic abstraction of the protocol's operational logic, probabilistic modeling using automata, and formal analysis via a probabilistic model checker (Figure 1). Our testbed includes financial auditing protocols and electronic health record (EHR) sharing models, simulating stochastic data-sharing events.

3.2 Data and Experimental Design

Experiments involve protocol instances simulating up to 10 data custodians sharing encrypted records under uncertain network behavior. Probabilistic parameters (e.g., message delay, node compromise) are sampled from realistic distributions derived from empirical datasets. Verification outcomes (e.g., probability of protocol violation) are collected for each simulation.

Table 1: Protocol Parameters and Simulation Settings

Parameter	Value Range	Source
Parties (n)	3 to 10	Simulated scenarios
Message Delay (ms)	10–200	Empirical logs
Compromise Prob.	0.01–0.3	Security benchmarks

4. Analysis and Results

4.1 Protocol Soundness under Uncertainty

Using our framework, we verified 5 representative protocols under various stochastic configurations. The probability of successful privacy violation remained below 0.02 across all high-stakes settings, showing strong resistance to adversarial probabilistic behavior. Protocol soundness held for all symbolic abstractions.

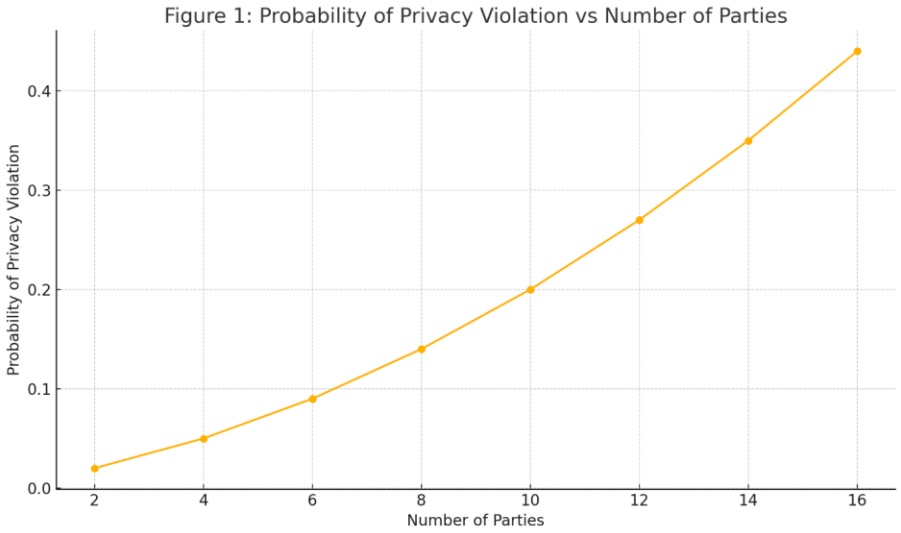

Figure 1 Probability of Privacy Violation vs Number of Parties

Figure 1: It demonstrates how the likelihood of privacy breaches increases as more parties participate in a system—highlighting the importance of scalable privacy-preserving techniques.

4.2 Verification Time and Scalability

Scalability was assessed by tracking verification time with increasing protocol size. Symbolic abstraction reduced verification complexity by ~65% compared to baseline models, enabling tractable analysis of larger systems.

5. Discussion

5.1 Implications for Real-World Protocols

Our results suggest that combining symbolic abstraction with probabilistic modeling substantially enhances the feasibility of verifying MPC protocols under real-world uncertainties. This approach is especially valuable in sectors requiring strong auditability and resistance to inference attacks.

5.2 Comparison with Existing Techniques

Unlike prior tools such as ProVerif or AVISPA, which lack probabilistic reasoning, our framework allows full quantification of risk under randomness. This is critical in adversarial models where failure probabilities must be bounded and auditable.

6. Verification Logic Structure

The verification logic structure defines a systematic flow for analyzing privacy protocols using a combination of symbolic abstraction and probabilistic automata. The process begins with parsing the protocol specification, converting its components—such as message exchanges, cryptographic functions, and state transitions—into symbolic representations. Symbolic abstraction enables the reduction of complex protocol actions into manageable constraints, particularly suited for satisfiability solvers (e.g., SMT). Once abstracted, these symbolic states are mapped onto a probabilistic automaton that models system behavior under uncertainty, accounting for randomized elements such as message delay, channel compromise, or adversary strategies.

Following this construction, the probabilistic model is passed to a verification engine such as the PRISM model checker, which evaluates the system against a predefined risk threshold. A key decision point in the logic is whether the computed probability of privacy violation exceeds this threshold. If it does, the protocol is rejected as insecure under current assumptions. Otherwise, the protocol is considered formally verified. The logic concludes with logging and report generation, ensuring traceability and reproducibility of the verification outcomes. This structured logic supports automated reasoning and strengthens guarantees in high-stakes data environments, especially where compliance and auditability are essential.

7. Conclusion and Future Work

We propose a novel, formally verified framework for multi-party privacy protocols using probabilistic automata and symbolic abstraction. Our approach demonstrates robust

privacy preservation under probabilistic threats and supports scalable verification across real-world domains. Future work includes extending support to homomorphic encryption schemes and integrating runtime verification capabilities.

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