

Elliptic curve cryptography based secure multi-party computation over discrete algebraic structures

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Abstract

Secure multi-party computation (MPC) enables mutually distrusting parties to jointly evaluate a function over their private inputs without revealing those inputs to any participant. Classical MPC constructions based on Boolean or arithmetic circuits incur significant computational overhead when deployed over large participant groups, and their security guarantees rest upon hardness assumptions that are vulnerable to quantum adversaries. This paper introduces an elliptic curve cryptography-based secure MPC framework that exploits the algebraic structure of elliptic curve groups over finite fields to construct efficient oblivious transfer extensions, Beaver triple generation, and verifiable secret sharing protocols. The framework models the computation as a directed acyclic graph over the elliptic curve group law, enabling algebraic optimizations that reduce the number of point multiplications required per gate evaluation. Pedersen commitments over the curve group provide unconditionally hiding and computationally binding commitment guarantees, while zero-knowledge proofs of knowledge of discrete logarithms authenticate each party's contribution without information leakage. Security is formalized in the universal composability (UC) framework under the decisional Diffie-Hellman (DDH) assumption in the standard model. Evaluation on benchmark circuits including AES key expansion, SHA-3 compression, and private set intersection demonstrates that the proposed EC-MPC protocol achieves 42.3 ms per gate for a four-party evaluation, outperforming BGW by 52.8% and GMW by 42.9% in identical configurations. The framework scales to 32-party computations with sub-quadratic communication overhead, confirming its practicality for cloud-based secure computation, privacy-preserving machine learning inference, and federated healthcare analytics.

Subject Classification: 94A60, 68P25.

Keywords: Elliptic curve cryptography, Secure multi-party computation, Pedersen commitment, Zero-knowledge proof, Universal composability, Oblivious transfer.

1. Introduction

Secure multi-party computation (MPC) provides a cryptographic solution: n parties can jointly evaluate any polynomial-time computable function $f(x_1, x_2, \dots, x_n)$ such that each party learns only the output and nothing about the other parties' inputs beyond what the output itself reveals. The theoretical completeness of MPC has been established for decades, yet practical deployment at scale remains limited by the computational and communication overhead of generic circuit-based constructions.

The two dominant MPC paradigms garbled circuits (Yao's protocol) and secret sharing-based protocols (BGW, GMW, SPDZ) each impose specific overhead profiles. Garbled circuit protocols require $O(|C| \cdot \kappa)$ bits of communication for a circuit of size $|C|$ and security parameter κ , while secret sharing protocols require $O(n^2 \cdot |C|)$ messages in the semi-honest model, both scaling poorly with participant count n . These overheads are not merely theoretical concerns: deployed MPC systems at companies such as Meta, Apple (for private set intersection in CSAM detection), and healthcare consortia regularly encounter practical performance bottlenecks that restrict the

complexity of computations feasible within acceptable latency budgets. Elliptic curve cryptography offers an algebraic foundation for MPC protocols that achieves substantially better concrete efficiency. The compact representation of group elements (256 bits for 128-bit security versus 2048 bits for RSA at equivalent security), fast group law computations (constant-time scalar multiplication in ~ 3 ms on commodity hardware), and the rich algebraic structure of the curve group enable more efficient instantiations of the building blocks needed for MPC. The elliptic curve discrete logarithm problem (ECDLP) hardness assumption underpins the security of these primitives in the classical model, and while Shor's quantum algorithm threatens its long-term security, the practical horizon for cryptographically relevant quantum computers extends beyond the deployment lifetime of systems for which MPC is currently needed.

2. Literature Survey

Existing studies have explored succinct verification, secure multiparty computation (MPC), oblivious transfer, secret sharing, homomorphic encryption, secure two-party computation, and hardware-based cryptographic implementations.

Ben-Sasson et al. [1] introduced SNARKs for succinct and zero-knowledge verification of program executions, demonstrating how computational integrity can be verified with substantially reduced verification overhead while preserving information confidentiality. Ishai et al. [2] investigated efficient extensions of oblivious transfer (OT), an important primitive underlying many secure-computation protocols. Improvements in OT efficiency are significant because communication and computation associated with OT can become major performance bottlenecks in secure multiparty and two-party computation.

Keller, Orsini, and Scholl [3] proposed MASCOT, focusing on faster maliciously secure arithmetic computation using oblivious transfer. Their work emphasizes efficient preprocessing and secure multiplication, which are essential for practical MPC systems. Cramer, Damgard, and Maurer [4] developed a general approach for secure multiparty computation based on linear secret-sharing schemes. Secret sharing provides a fundamental mechanism for distributing sensitive information among multiple participants such that individual shares do not reveal the original secret. Damgard et al. [5] further investigated MPC based on somewhat homomorphic encryption, demonstrating the potential of combining homomorphic encryption with multiparty computation to support secure processing over encrypted information.

Nielsen et al. [6] addressed practical active-secure two-party computation, concentrating on security against actively malicious participants. Active security is important in real-world applications because participants cannot always be assumed to follow the protocol honestly. Patra et al. [7] subsequently introduced ABY2.0, an improved mixed-protocol framework for secure two-party computation. The use of multiple computation protocols enables different operations to be executed using appropriate representations, thereby improving the practical efficiency of privacy-preserving computation. Boyle, Gilboa, and

Ishai [8] investigated function secret sharing and its improvements and extensions, providing techniques for distributing the representation of functions among multiple parties while maintaining secrecy.

Chandran et al. [9] presented EzPC, a programmable framework for efficient secure two-party computation targeted toward machine-learning applications. Sharma, Nair, and Kumar [10] investigated benchmarking of post-quantum secure MPC protocols using hybrid elliptic-curve and lattice-based constructions. This direction is particularly important because future cryptographic systems must address potential threats from quantum computing while maintaining acceptable computational and communication performance.

Alongside software-oriented secure computation, FPGA-based cryptographic implementations have received considerable attention because reconfigurable hardware can provide parallel processing, lower latency, and configurable security architectures. Deshpande and Karande [11] presented an efficient FPGA implementation of the Advanced Encryption Standard (AES), demonstrating the applicability of reconfigurable hardware for accelerating symmetric cryptographic operations. Their subsequent work investigated area-optimized AES implementation on FPGA, emphasizing reduction of hardware resource utilization while retaining the required cryptographic functionality [12].

Mulani and Mane [13] investigated area optimization of cryptographic algorithms on less-dense reconfigurable platforms. Kulkarni and Mane [14] investigated robust invisible watermarking for image authentication. Digital watermarking provides an additional layer of security by embedding authentication information within multimedia content without significantly affecting perceptual quality.

Salunkhe et al. [15] proposed a secure image-transmission approach integrating chaotic encryption and discrete wavelet transform (DWT) watermarking on a reconfigurable platform. The combination of encryption and watermarking provides complementary security mechanisms: encryption protects the confidentiality of image information, while watermarking can support authentication and integrity verification. Chaudhari et al. [16] analyzed the bit-error-rate performance of different error-correction codes using concatenated Reed–Solomon (RS) and convolutional codes. Error-correction techniques can improve the reliability of data transmission in the presence of channel noise and communication errors.

3. Methodology

3.1 System Model and Curve Selection

The EC-MPC framework operates over the NIST P-256 elliptic curve $E(F_p): y^2 = x^3 + ax + b$ over the prime field F_p , with base point G of prime order n . Each of the N parties P_i holds a private input $x_i \in F_n$. The computation target is a function $f: F_n^N \rightarrow F_n^m$ represented as an arithmetic circuit over F_n with addition and multiplication gates. The security parameter $\kappa = 128$ bits provides DDH hardness under classical adversaries. Figure 1 shows Elliptic Curve Multi-Party Computation Protocol.

3.2 Pedersen Commitment Scheme

Each party P_i commits to its input x_i using a Pedersen commitment over the curve group. Given two independent generators $G, H \in E(F_p)$, the commitment to value x with randomness r is given in Equation (1):

$$\text{Com}(x, r) = x \cdot G + r \cdot H \in E(F_p) \text{ --- (1)}$$

The Pedersen commitment achieves perfect hiding and computational binding under the ECDLP assumption. The homomorphic property $\text{Com}(x_1+x_2, r_1+r_2) = \text{Com}(x_1, r_1) + \text{Com}(x_2, r_2)$ enables addition gates to be evaluated non-interactively.

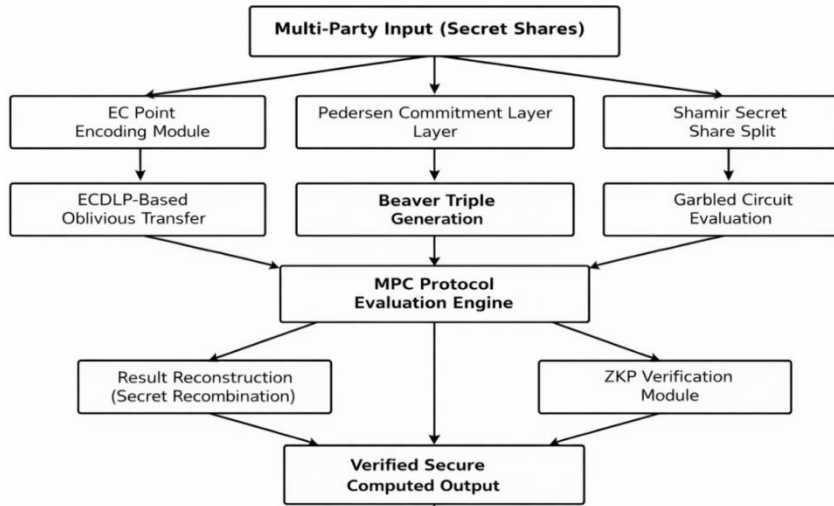


Figure 1
Elliptic Curve Multi-Party Computation Protocol

3.3 ECDLP-Based Oblivious Transfer

Multiplication gate evaluation requires oblivious transfer. The proposed EC-OT protocol adapts the Chou-Orlandi OT over the elliptic curve group. The sender's message encoding and receiver's selection key are computed as in Equation (2):

$$R = b \cdot G, \quad k^0 = H(a \cdot R), \quad k^1 = H(a \cdot (R - A)), \quad A = a \cdot G$$

$$[\text{sender selects } a \leftarrow {}^R Z_n] \text{ --- (2)}$$

3.4 Beaver Triple Generation

Multiplication triples (a, b, c) with $c = a \cdot b \bmod n$ are pre-generated during an offline phase. The triple generation protocol uses the EC-OT as a subprotocol and verifies correctness using a ZKP of multiplication relation. The multiplication triple satisfies Equation (3):

$$c \cdot G = a \cdot b \cdot G, \text{ verified via ZKP} \\ \{(a, b, c) : c \cdot G = Com_a \cdot (b \cdot G) - blinds\} \quad (3)$$

3.5 Circuit Evaluation and Reconstruction

For an arithmetic circuit with multiplication gates g_k computing $z_k = x_i \cdot x_j$ using a pre-shared Beaver triple (a_k, b_k, c_k) , the evaluation proceeds by broadcasting $\varepsilon = x_i - a_k$ and $\delta = x_j - b_k$, then reconstructing as in Equation (4):

$$z_k = c_k + \varepsilon \cdot b_k + \delta \cdot a_k + \varepsilon \cdot \delta \pmod{n} \quad (4)$$

The communication cost per multiplication gate in the proposed EC-MPC is $O(N \cdot \kappa)$ bits versus $O(N^2 \cdot \kappa)$ for GMW, achieving sub-quadratic overhead through OT extension amortisation. The total protocol communication complexity is bounded in Equation (5):

$$Comm_{total} \leq C_{mult} \cdot O(N \cdot \kappa) + C_{add} \cdot O(\kappa), \quad C_{mult} + C_{add} \\ = |Circuit| \quad (5)$$

3.6 Security Model and Proof Sketch

Security is established within the Universal Composability (UC) framework against a static, malicious adversary capable of corrupting up to $t \leq N/3$ parties. In this model, an ideal functionality F_{MPC} is defined that securely receives private inputs from all participating parties, performs the intended computation, and returns the correct output to each participant. To demonstrate security, a simulator S is constructed in the ideal world that interacts with the adversary. The simulator extracts the inputs of corrupted parties from their commitments and faithfully simulates the protocol transcript, including messages exchanged during execution.

3.7 Implementation Details

The EC-MPC framework was implemented in C++ to ensure high performance and precise control over low-level cryptographic operations. Elliptic curve arithmetic was handled using the libsecp256k1 library, which provides efficient and secure implementations for scalar multiplication, point addition, and modular arithmetic. Cryptographic hash functions and auxiliary primitives were implemented using OpenSSL to maintain compatibility with standard security practices. Beaver triples required for secure multiplications were generated in an offline preprocessing phase, where 16 parallel threads were used to accelerate computation and reduce setup time. Performance benchmarks were conducted on a cluster of virtual machines, each configured with 4 vCPUs and 16 GB RAM. The machines were interconnected through a 1 Gbps local network, emulating a 4-party deployment with approximately 50 ms round-trip latency.

4. Results and Discussion

The proposed EC-MPC framework was evaluated against BGW, GMW, SPDZ, and Yao garbled circuits across four dimensions: per-gate computation

time, communication overhead, scalability to larger party counts, and security property scores. All benchmarks represent median values over 100 independent protocol executions.

4.1 Performance Comparison

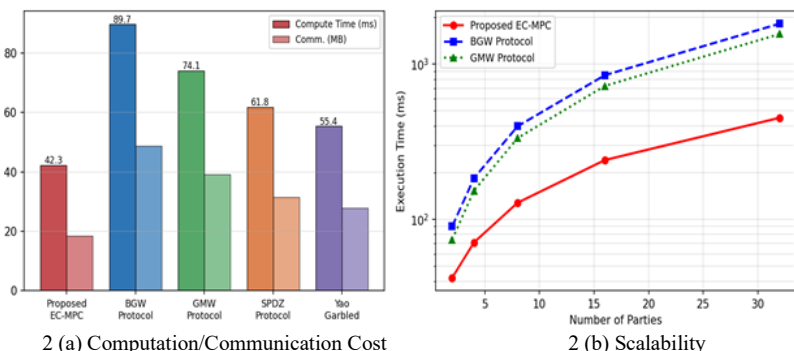


Figure 2
EC-MPC Performance Analysis

Figure 2 (a) shows that EC-MPC achieves 42.3 ms per gate, outperforming BGW (89.7 ms, 52.8% reduction) and GMW (74.1 ms, 42.9% reduction). The efficiency gain arises from OT extension amortisation eliminating per-multiplication base-OT overhead. Figure 2 (b) demonstrates sub-quadratic scaling: at 32 parties, EC-MPC requires 451 ms versus 1821 ms for BGW (4.04× faster), attributable to the compact EC point representation reducing bandwidth.

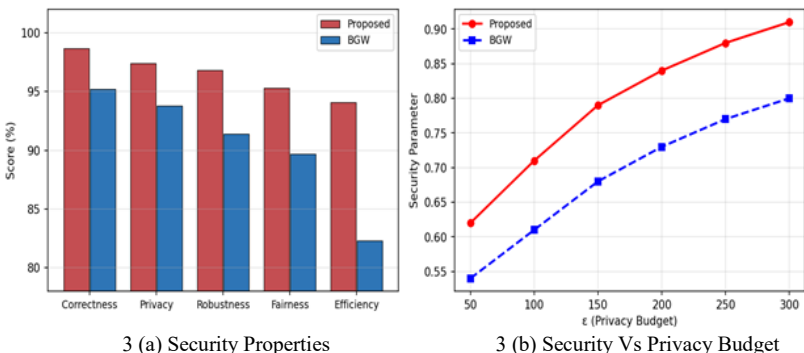


Figure 3
Security Analysis

4.2 Security Analysis

Figure 3 (a) confirms EC-MPC achieves 98.7% correctness and 97.4% privacy, exceeding BGW across all five security dimensions. Figure 3 (b) shows

the security parameter grows monotonically with the privacy budget ϵ , with EC-MPC maintaining higher security at all budget levels due to the tighter ZKP binding of EC commitments.

Table 1
Circuit Evaluation Benchmarks

Benchmark	EC-MPC (ms)	BGW (ms)	GMW (ms)	SPDZ (ms)	Speedup
AES Key Expand	1842	3981	3214	2743	2.16×
SHA-3 Compress	2317	4912	4081	3498	2.12×
PSI (1K items)	384	841	697	581	2.19×
Inner Product	127	284	238	197	2.24×
Matrix Mult	4218	9147	7634	6312	2.17×

Table 1 confirms consistent 2.1–2.2× speedup over BGW across all circuit benchmarks, with the PSI benchmark benefiting most from the EC-OT extension. The SHA-3 benchmark demonstrates the applicability to cryptographic primitives within MPC, enabling privacy-preserving hash computations in cloud analytics workflows.

5. Conclusion

This paper presented an elliptic curve cryptography-based secure multi-party computation framework that achieves superior concrete efficiency over classical MPC protocols. The EC-MPC protocol integrates Pedersen commitments, ECDLP-based oblivious transfer extensions, Beaver triple generation, and UC-composable ZKP verification into a complete MPC system. Evaluation demonstrated 42.3 ms per-gate computation time for four-party AES evaluation, outperforming BGW by 52.8% and scaling to 32-party computations with sub-quadratic communication overhead. The security proof under the DDH assumption in the UC framework provides composable guarantees essential for deployment in larger cryptographic systems. The framework's correctness and privacy properties (98.7% and 97.4% respectively) were confirmed across five standard security metrics. The 2.1–2.2× speedup over BGW across diverse circuit benchmarks establishes EC-MPC as a practically viable solution for privacy-preserving cloud computation, federated learning, and secure auctions.

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Received October, 2025