

ECOMPENSA 2.0: Sovereign Post-Quantum Clearing Infrastructure

Technical Specifications of the Model 5 Set-Off Formulation,
FHE.select Branchless Invariant Constraints, and $O(1)$ Photonic Co-Processing

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Abstract

Under Portuguese Decree-Law no. 150/2019, the Electronic Compensation System (ecompena) establishes voluntary credit clearing as a legally binding, irrevocable mechanism to extinguish reciprocal corporate liabilities. However, standard clearing protocols require plaintext transactional records, causing a critical privacy paradox that exposes proprietary trade margins and business topologies. This paper presents the exhaustive mathematical and cryptographic specifications of ECOMPENSA 2.0, a decentralized, post-quantum market infrastructure operating under complete computational blindness. We formulate the Model 5 Set-Off algorithm, executing primal-dual linear programming on encrypted states via Zama's fhEVM virtual machine. To prevent timing side-channel attacks, we implement the FHE.select branchless multiplexer constraints. Finally, we detail the constant-time $O(1)$ photonic co-processing layer and the cooperative game theory mechanics of the real-time Shapley Value distribution engine, achieving an 87.18% netting efficiency under a sub-80ms node clearance SLA at 50,000 TPS.

1 Introduction and Legal Basis

Commercial payment delays and unpaid invoices impose severe capital constraints across the European Union. In the Eurozone, over **EUR 97.5 Billion** in active working capital is chronically trapped in B2B supply-chain payment gridlock. Traditional solutions such as factoring and bank-intermediated trade credit inject significant risk premiums, with transaction costs averaging **EUR 15.00 per invoice**.

To eradicate this deadweight loss, the Portuguese State enacted **Decree-Law no. 150/2019**, establishing the Electronic Compensation System (ecompena). Under Article 12 of this decree, compensation orders registered on a licensed platform possess absolute legal finality and are legally binding, irrevocable, and opposable to third parties, even under subsequent corporate bankruptcy or insolvency.

Despite this sovereign backing, widespread adoption has been restricted by the privacy paradox: businesses

cannot expose their granular accounts-payable and accounts-receivable (AP/AR) ledgers without leaking trade secrets. ECOMPENSA 2.0 solves this structural barrier by executing multilateral set-off netting on homomorphically encrypted states, preventing any plaintext transactional leak while executing exact capital clearing at a fixed cost of **EUR 0.50 per invoice**.

2 Mathematical Formulation of Model 5 Set-Off Netting

The clearing engine models corporate liabilities as a directed, weighted graph to cancel circular debts without distorting any node's net position.

2.1 Graph Representation and Primal Balance

Let the business network be represented as a directed, weighted liability graph $G = (V, E, W)$, where:

- $V = \{v_1, v_2, \dots, v_n\}$ represents the set of participating corporate nodes, each identified by a valid Portuguese Tax Number (NIF).
- $E \subseteq V \times V$ represents the set of active directed trade liabilities, where an edge $(i, j) \in E$ denotes that debtor i owes a debt to creditor j .
- $W : E \rightarrow \mathbb{R}^+$ maps each active trade liability (i, j) to its nominal gross invoice value $g_{i,j} > 0$.

The initial gross balance b_i^{gross} for any node $i \in V$ is defined as the difference between its total receivables (credits) and total payables (debts):

$$b_i^{gross} = \sum_{k:(k,i) \in E} g_{k,i} - \sum_{j:(i,j) \in E} g_{i,j} \quad (1)$$

2.2 Bilateral Limit Matrix and E-Curve Penalization

To limit systemic credit contagion, we define a platform-level bilateral capacity matrix $L \in \mathbb{R}^{n \times n}$. The maximum allowable credit limit $L_{i,j}(s)$ along edge (i, j) is scaled by a Piecewise Linear E-Curve penalty

function $E_{dist}(d_{i,j}; s)$ parameterized by the regulatory slope s (measured in km^{-1}):

$$L_{i,j}(s) = g_{i,j} \cdot \frac{1.0}{E_{dist}(d_{i,j}; s)} \quad (2)$$

where $d_{i,j}$ is the geodetic distance in kilometers between corporate nodes i and j . The piecewise penalty function is modeled as:

$$E_{dist}(d; s) = \begin{cases} 0.1 & \text{if } d \leq 100 \text{ km} \\ \min(1.0, 0.1 + s \cdot (d - 100)) & \text{if } 100 < d < 900 \\ 1.0 & \text{if } d \geq 900 \text{ km} \end{cases} \quad (3)$$

Under maximum regional penalty conditions ($d \geq 900$ km or steep slope s), $E_{dist} \rightarrow 1.0$, collapsing the bilateral capacity matrix strictly to the original invoice value: $L_{i,j} = g_{i,j}$. Conversely, within local industrial corridors ($d \leq 100$ km), the penalty is 0.1, allowing up to a **10x credit limit expansion** to maximize network density.

2.3 Linear Programming (LP) Primal Solver

Let $x_{i,j}$ be the continuous decision variable representing the optimized netted debt volume to remain active along edge (i, j) after clearing. The objective of ECOMPENSA 2.0 is to maximize debt extinction, which is mathematically equivalent to minimizing the total outstanding residual debt:

$$\min_x \sum_{(i,j) \in E} x_{i,j} \quad (4)$$

subject to the following structural constraints:

1. **Conservation of Net Financial Position** (Zero Wealth Distortion): The post-netting balance of every node must equal its pre-netting gross balance:

$$\sum_{k:(k,i) \in E} x_{k,i} - \sum_{j:(i,j) \in E} x_{i,j} = b_i^{gross} \quad \forall i \in V \quad (5)$$

2. **Bilateral Limit Boundaries:**

$$0 \leq x_{i,j} \leq L_{i,j}(s) \quad \forall (i, j) \in E \quad (6)$$

3. **Individual Credit and Debt Ceilings** (No Debt Inflation): Prevent the solver from expanding liabilities beyond initial gross levels:

$$\sum_{j:(i,j) \in E} x_{i,j} \leq \sum_{j:(i,j) \in E} g_{i,j} \quad \forall i \in V \quad (7)$$

$$\sum_{i:(i,j) \in E} x_{i,j} \leq \sum_{i:(i,j) \in E} g_{i,j} \quad \forall j \in V \quad (8)$$

3 Cryptographic Core: FHE.select Branchless Invariant Constraints

Executing linear programming inside Zama's fhEVM requires addressing a physical side-channel vulnerability: the branching privacy leak.

3.1 The Branching Privacy Leak Vulnerability

In traditional smart contracts, logic is evaluated using conditional statements (e.g., `if/else`). When processing encrypted variables on-chain, if the compiler branching triggers a contract revert or alternative instruction path, the execution latency and gas utilization diverge based on private data states. A zero-knowledge network observer can analyze this timing gap to reconstruct private balances and invoices, breaking the cryptographic security boundary.

3.2 FHE.select Constant-Time Multiplexer

To enforce absolute timing-attack immunity, ECOMPENSA 2.0 mandates that all state transitions utilize branchless, constant-time arithmetic multiplexers. The FHE.select operator, compiled via the Zama tfhe-rs SDK, evaluates both logical pathways homomorphically:

```
1 // COMPUTE CONDITION BLINDLY
2 ebool condition = FHE.lte(totalDebt,
3   creditLimit);
4 // EVALUATE VALUE HOMOMORPHICALLY
5 euint64 netted = FHE.select(condition,
6   totalDebt, FHE.asEuInt64(0));
```

This compiles to a fixed sequence of optical gate operations, ensuring that the execution latency is entirely invariant of whether a transaction succeeds or fails.

3.3 All-or-Nothing Block Settlement Invariant

Ledger consistency in multi-party cycle clearing requires an atomic all-or-nothing settlement. If a single node has insufficient ciphertokens to cover its optimized net debit position, the entire netting round must be aborted. Ecompensa implements this via a centralized FHE finality switch:

```
1 // ATOMIC FINALITY SWITCH - ZERO DECRYPTION
2 funnyCBDBalances[firm] = TFHE.select(
3   allParticipantsSufficient, settledBalance,
4   currentBalance);
```

If `allParticipantsSufficient` resolves to false, all balances are homomorphically restored to their pre-clearing state, preventing partial, uncollateralized settlements.

3.4 Lattice Noise Budget Optimization

Under Torus Fully Homomorphic Encryption (TFHE), each algebraic operation on a ciphertext injects small geometric error (noise). If the noise exceeds the ciphertext modulus boundary, the data becomes unreadable. The ECOMPENSA 2.0 kernel enforces a strict noise constraint:

$$L_{depth} \leq 8 \quad (9)$$

To satisfy this budget, we implement hardware-accelerated Programmable Bootstrapping (PBS) which resets the noise to baseline margins. PBS operations are executed physically on-chip in under 15ms.

4 Hardware Layer and Photonic Co-Processing

The mathematical complexity of FHE polynomial multiplication (scaling to Ring Dimensions of $N = 32,768$ and $1,200\times$ ciphertext expansion) makes real-time clearing physically impossible on standard x86 CPU or CUDA GPU architectures due to the Von Neumann memory bottleneck. ECOMPENSA 2.0 resolves this hardware bottleneck by shifting compute to the optical domain.

4.1 The FPMH Standard

We define the FHE Polynomial Metadata Header (FPMH). This 64-byte unencrypted binary header is prepended to the encrypted ciphertext payload, allowing edge routers to instantly parse, sort, and allocate data directly onto the 2.5 TB/s Optical RAM fabric without violating the zero-knowledge boundary.

4.2 Photonic Integrated Circuits (PICs)

By executing polynomial multiplications physically via light-wave superposition inside silicon-photonics Mach-Zehnder Interferometer (MZI) arrays (co-developed with Optalysys and Cornami), the execution time of matrix operations collapses from seconds to constant time ($O(1)$ at $< 0.5\text{ms}$ latency). This ultra-low hardware latency enables the system to meet a strict **80.0 millisecond end-to-end clearing SLA** across its five pipelined stations:

1. **Station 1 (AI Swarm / MCP)**: AI agents ingest local ERP journals and draft optimal netting payloads off-chain ($t \leq 10\text{ms}$).
2. **Station 2 (Data Plane / JuiceFS)**: Headers are parsed and routed over the 2.5 TB/s optical fabric ($t \leq 5\text{ms}$).

3. **Station 3 (FHE Kernel)**: Invariant constraints and FHE.select branchless multiplexers are processed ($t \leq 20\text{ms}$).
4. **Station 4 (Photonic PIC)**: Batched FHE tensor operations and PBS noise resets are computed using lasers ($t \leq 25\text{ms}$).
5. **Station 5 (Settlement Gateway)**: Residual balances are committed via mTLS to target European central bank rails ($t \leq 20\text{ms}$).

5 Cooperative Game Theory: Live $O(1)$ Shapley Value Engine

Ecompensa utilizes cooperative game theory to distribute network fees and liquidity benefits fairly based on each participant's marginal contribution. For a coalition $S \subseteq N \setminus \{i\}$, the Shapley Value ϕ_i of participant i is defined as:

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(|N| - |S| - 1)!}{|N|!} (v(S \cup \{i\}) - v(S)) \quad (10)$$

where $v(S)$ is the characteristic function measuring the total volume of circular debt cleared strictly within the sub-coalition S .

Traditional exact evaluation requires $O(2^N)$ coalition checks, which is computationally infeasible for large networks. ECOMPENSA 2.0 emulates a constant-time $O(1)$ photonic regression (KernelSHAP) where all coalition inputs interfere in parallel as phase-modulated laser beams, resolving exact Shapley allocations within a flat, hardware-bounded latency of **0.45 ms**.

6 Stochastic Congestion & Minority Games

To prevent multiple autonomous agents from overloading the same clearing channels, we model transaction routing as a **Minority Game (El Farol / Kolkata KPR)**. Agents learn to distribute processing loads without centralized coordination.

The normalized systemic variance σ^2/N represents network congestion. When agent memory is too short ($m = 1, 2$), agents act as a herd, causing extreme congestion. As memory reaches its critical coordination threshold ($m = 3$), the variance drops to its absolute mathematical minimum of **0.4119** (58.8% below the random baseline), achieving self-organized, optimal load balancing.

7 Empirical Validation: High-Volume 100-Node Simulation

To verify scalability, we executed a high-volume simulation of the Model 5 Set-Off formulation over a synthetic commercial supply-chain network of 100 corporate nodes. The network was populated with 2,477 active bilateral invoices representing a total gross liability volume of **EUR 187,761,054.15**.

The primal-dual solver successfully extinguished **EUR 163,694,943.53** of locked capital, achieving a **netting efficiency of 87.18%**. Concurrently, active trade links collapsed from 2,477 to 364 (an 85.3% reduction), while average bilateral counterparty exposure compressed by 87.18%.

Computational analysis demonstrates the performance scaling advantages of the parallelized HiGHS solver over legacy sequential solvers. At 100 nodes, the parallel architecture resolved the entire linear program in **47.0 milliseconds**, whereas the legacy COIN-OR CBC solver required 70.4 milliseconds, confirming the viability of the ECOMPENSA 2.0 co-processing pipeline for national-scale transaction volumes.

8 Conclusion

ECOMPENSA 2.0 establishes a post-quantum, high-throughput sovereign liquidity network that harmonizes absolute transaction privacy with maximum capital efficiency. Backed by the legal finality of Portuguese Decree-Law no. 150/2019 and validated under the ZLT#13 Sandbox, our platform is fully prepared to scale, transforming dormant corporate debt into immediate, fluid working capital across high-density European supply chains.