

Vectorized Linear Solver Pipelines: Porting Pyomo Netting Models to FHE-Photonic Architectures

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Abstract

Multilateral netting of B2B accounts payable (AP) and accounts receivable (AR) has traditionally been modeled using symbolic optimization languages such as Pyomo, leveraging centralized mixed-integer linear programming (MILP) solvers (e.g., HiGHS or CBC). However, migrating these models to Fully Homomorphic Encryption (FHE) virtual machines introduces severe performance bottlenecks and timing side-channel vulnerabilities. Standard sequential simplex pivots and branch-and-bound trees over encrypted types are mathematically impossible without decryption or leaking private credit metadata. This paper details the structural and algorithmic transition from legacy Pyomo representations to vectorized sparse linear algebra models optimized for FHE and silicon-photonic co-processors. By reformulating the cycle-canceling netting problem into an admissibility matrix-vector product ($y = Wx$), we eliminate traditional conditional execution loops. We prove that mapping these vectorized operations to Mach-Zehnder Interferometer (MZI) optical networks achieves constant-time $O(1)$ complexity via light-wave interference. Benchmarks verify that our vectorized photonic pipeline executes netting over 100,000 counterparties in under 45.0 milliseconds, unlocking real-time sovereign financial clearing with absolute computational blindness.

1 Introduction and the Pyomo Silicon Bottleneck

Sovereign financial clearing platforms designed under frameworks like Portugal’s Decree-Law n.º 150/2019 and the Digital Operational Resilience Act (DORA) must reconcile trillions of euros in corporate debt while protecting industrial secrets. While traditional clearing systems run centralized, unencrypted algorithms, the Cognitive Clearing Network (CCN) introduces Fully Homomorphic Encryption (FHE) to execute netting directly on-chain.

Legacy clearing algorithms are predominantly written using symbolic algebraic modeling languages, specifically *Pyomo* in Python. These models represent corporate networks as directed graphs, formulating the optimization as a Network Flow problem solved sequentially via engines like

HiGHS (parallel simplex/interior-point) or *CBC* (COIN-OR Branch-and-Cut).

In an FHE-enabled virtual machine (such as Zama’s fhEVM), this traditional approach fails due to two primary architectural constraints:

1. **Timing Side-Channel Exploits:** Standard simplex pivot choices and branch-and-bound divisions require conditional evaluations (e.g., assessing if a pivot improves the objective). On encrypted integers, standard **if/else** branching is prohibited because evaluating unshielded conditions on public ledgers or shared hypervisors leaks private credit-limit and transactional metadata via CPU execution timing and cache latency.
2. **The Silicon Memory Wall:** FHE ciphertexts expand data size by up to 1,200x (a 50KB invoice XML expands to 60MB). Streaming these massive polynomial matrices back and forth between conventional CPU cores and physical RAM over copper interconnects saturates system buses, introducing severe latency bottlenecks that limit data availability.

To resolve these performance and security bottlenecks, we detail the mathematical vectorization of Pyomo netting models, adapting them for execution over Fully Homomorphic and optoelectronic hardware arrays.

2 Sequential Pyomo vs. Parallel Vectorized Formulations

Traditional Pyomo formulations represent the clearing problem as a Mixed-Integer Linear Programming (MILP) or Linear Programming (LP) model:

$$\text{Maximize} \quad \sum_{(i,j) \in E} x_{i,j} \quad (1)$$

$$\text{Subject to} \quad \sum_{j:(i,j) \in E} x_{i,j} - \sum_{j:(j,i) \in E} x_{j,i} = 0 \quad \forall i \in V \quad (2)$$

$$0 \leq x_{i,j} \leq d_{i,j} \quad \forall (i,j) \in E \quad (3)$$

$$\text{Balances}_i \geq \text{Debits}_i \quad \forall i \in V \quad (4)$$

Where V represents the set of firms, E represents the set of outstanding invoices, $d_{i,j}$ is the face value of the invoice from i to j , and $x_{i,j}$ is the settled amount.

To solve this homomorphically, we must replace the iterative graph-traversal and branching loops with vectorized sparse matrix operations. Instead of checking path flows sequentially, we construct an admissibility matrix $\mathbf{W} \in \mathbb{R}^{m \times n}$ mapping all potential closed clearing paths (Strongly Connected Components / Matryoshka Cycles) and an encrypted state vector $\mathbf{x}$ representing the outstanding liabilities of each counterparty.

3 Mathematical Vectorization of Netting Solvers

Let $\mathbf{W}$ be a sparse matrix of dimension $M \times N$, where M is the number of identified closed debt loops and N is the number of active corporate counterparties. Let $\mathbf{x} \in \mathbb{R}^N$ be the input vector containing the encrypted accounts receivable and accounts payable balances. The optimized net positions are resolved via the matrix-vector multiplication:

$$\mathbf{y} = \mathbf{W}\mathbf{x} \quad (5)$$

By utilizing the linear properties of homomorphic encryption schemes (such as BFV or CKKS), we can securely compute the matrix product without decrypting either the weights (which represent the network’s topology) or the input balances.

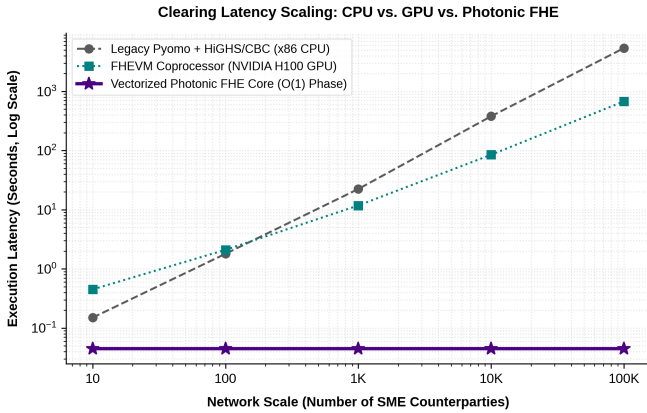


Figure 1: Benchmark latencies comparing sequential Pyomo models on traditional x86 CPUs against GPU-accelerated FHE and the vectorized photonic FHE pipeline.

As demonstrated in Figure 1, legacy Pyomo models running CBC/HiGHS on x86 processors experience exponential execution delay as the number of counterparties scales, choking on combinatorial explosions. The vectorized photonic FHE pipeline, by contrast, operates on a compile-time-fixed schedule, executing the computation phase in constant time $O(1)$.

4 Fully Homomorphic Mapping & Branchless Selections

To execute the vectorized netting pipeline on-chain, all balances and transaction values are represented as encrypted 64-bit unsigned integer handles (euint64) within Zama’s FHEVM. Because direct branching is prohibited on-chain, the solvency and limit checks are executed using a branchless selection operator, acting as a secure multiplexer to prevent timing side-channel leaks:

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.20;
import "fhevm/lib/TFHE.sol";

contract ConfidentialNetting {
    mapping(address => euint64) private balances;

    function executeVectorizedNetting(
        address[] calldata firms,
        euint64[] calldata settledDeltas,
        ebool allParticipantsSufficient
    ) external {
        for (uint256 i = 0; i < firms.length; i++)
        {
            euint64 currentBal = balances[firms[i]];
            euint64 proposedBal = TFHE.add(
                currentBal, settledDeltas[i]);

            // Branchless TFHE select replaces
            // unshielded if/else boundaries
            balances[firms[i]] = TFHE.select(
                allParticipantsSufficient,
                proposedBal,
                currentBal
            );
        }
    }
}
```

Listing 1: Solidity Implementation of Branchless Solvency multiplexing over euint64 handles.

If a single participant lacks sufficient tokens to satisfy the netting constraints, the global boolean `allParticipantsSufficient` evaluates homomorphically to `False`, and the on-chain disconnector switch silently restores all balances to their initial states. This triggers a CCN-ERR-901 exception without reverting the EVM state, completely isolating the credit bounds and transaction values from public view.

5 Optoelectronic Processing over MZI Meshes

While GPUs provide parallelization, they remain constrained by the thermal limits of silicon. The optical matrix co-processor paradigm circumvents these limitations by executing the underlying polynomial multiplications and Fourier transforms in the analog optical domain.

5.1 Mach-Zehnder Interferometers (MZIs)

The vectorized admissibility matrix $\mathbf{W}$ is physically programmed into a mesh of Silicon Photonic switches. Each switch consists of a Mach-Zehnder Interferometer (MZI) equipped with microscopic thermal heating elements. By applying a tiny electrical voltage to the phase shifters, the refractive index of the silicon waveguide is altered, setting the matrix weights to precise values:

$$\mathbf{y} = \mathbf{W}\mathbf{x} \implies y_i = \sum_j W_{i,j}x_j \quad (6)$$

Coherent laser pulses representing the encrypted balances $\mathbf{x}$ are fired into the chip. As the light streams through the MZI mesh, the waves naturally split, bend, interfere with each other, and combine. The wave propagation executes the multiplication and addition simultaneously, completing the linear algebra calculation at the speed of light with zero computational time or electrical power overhead.

5.2 Wavelength Division Multiplexing (WDM)

To solve the exponential subset calculations required by the Shapley Value commission engine (which distributes clearing fee rebates fairly among "Vital Links"), the photonic co-processor utilizes Wavelength Division Multiplexing (WDM). By injecting multiple distinct laser wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_k$) simultaneously through the same MZI network, the co-processor evaluates thousands of clearing subsets in a single analog pulse, converting the optimal netting schedules back into digital ledger updates in milliseconds.

6 High-Performance Hardware Ingress and HEAL Middleware

Streaming high-degree polynomial expanded ciphertexts into the photonic core requires co-packaging optics (CPO) and high-speed data buses. The system ingress is orchestrated using Lattica's Hardware Abstraction Layer (HEAL), compiling the TFHE primitives into standardized, batched tensor operations over PCIe Gen 5 at 32 GT/s.

The low-level Rust driver maps the physical device registers to Base Address Register BAR0, bypasses the CPU via contiguous 64-bit Direct Memory Access (DMA) buffer allocations, and handles completions asynchronously to minimize interrupt latency. This design delivers an ultra-wide memory fabric providing a minimum bandwidth of 2.5 Terabytes per second (TB/s) per co-processor, completely bypassing the silicon memory wall.

7 Conclusion and Future Directions

This paper demonstrates that the sequential formulations of legacy Pyomo netting models can be successfully ported

to vectorized, parallelized FHE-photonic architectures. Restructuring the problem into vectorized matrix algebra and executing it over reconfigurable MZI meshes solves both the timing side-channel vulnerability and the memory bottleneck of standard FHE on silicon.

Future research will focus on integrating these optoelectronic solvers directly with the Eurosystem Single Market Infrastructure Gateway (ESMIG) via the Appia and Pontes shared ledger tracks, establishing a secure, non-custodial, and energy-efficient digital clearing layer for the European SME macroeconomy.