

BitVM3: Efficient Computation on Bitcoin

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Abstract

BitVM3 is a protocol for verifying SNARK proofs on Bitcoin that dramatically reduces the on-chain footprint of its predecessor, BitVM2. By leveraging optimistic computation with a garbled circuit, BitVM3 shifts the burden of verification off-chain. This design enables an evaluator to generate a compact fraud proof in the event of a dispute. The resulting on-chain transactions are highly efficient: the assertion transaction is approximately 56 kB, while the disproval transaction is just 200 bytes, reducing the on-chain cost of a dispute by over 1,000 times compared to the previous design.

1 Introduction

BitVM3 significantly enhances the on-chain efficiency of SNARK proof verification on Bitcoin. It addresses the primary drawback of BitVM2, where the ‘assertTx’ and ‘disproveTx’ were large (2-4 MB). In contrast, BitVM3 reduces the ‘assertTx’ to about 56 kB and the ‘disproveTx’ to a mere 200 bytes.

The core principle remains optimistic computation and the overall transaction graph remains unchanged. However, instead of using Bitcoin Script for on-chain computation, BitVM3 employs a garbled circuit to shift the computation off-chain. This circuit is designed to conditionally reveal a secret, which acts as a fraud proof, only if the garbler provides an invalid SNARK proof. This approach builds upon ideas from Jeremy Rubin and Liam Eagen.

2 Computing Gate Labels

The garbling scheme is founded on an RSA-based system.

- **Public Parameters:** The garbler selects and publishes an RSA modulus N and five public exponents: e, e_1, e_2, e_3, e_4 . These exponents must be invertible modulo $\phi(N)$, and for performance, small primes (e.g., 3, 5, 7, 11, 13) are suitable. Let their inverses be d, d_1, d_2, d_3, d_4 . Additionally, the derived exponent $h \equiv (e_1 e_4 d_2 - e_3) \pmod{\phi(N)}$ must also be invertible.
- **Label Generation:** Using the secret trapdoor $\phi(N)$, the garbler computes the secret input wire labels $a_0, a_1, b_0, b_1 \in (\mathbb{Z}/N\mathbb{Z})^*$ by solving the following system for output labels c_0, c_1 :

$$\begin{aligned} a_0^e \cdot b_0^{e_1} &\equiv c_0 \pmod{N} \\ a_0^e \cdot b_1^{e_2} &\equiv c_0 \pmod{N} \\ a_1^e \cdot b_0^{e_3} &\equiv c_0 \pmod{N} \\ a_1^e \cdot b_1^{e_4} &\equiv c_1 \pmod{N} \end{aligned}$$

The knowledge of $\phi(N)$ allows the garbler to efficiently find a unique solution. The explicit solutions for the secret input labels are:

$$\begin{aligned} b_0 &\equiv (c_1 c_0^{-1})^{h^{-1}} \pmod{N} \\ b_1 &\equiv b_0^{e_1 d_2} \pmod{N} \\ a_0 &\equiv c_0^d \cdot b_0^{-e_1 d} \pmod{N} \\ a_1 &\equiv c_0^d \cdot b_0^{-e_3 d} \pmod{N} \end{aligned}$$

2.1 Setup for Tree Circuits (Backward Pass)

For a circuit with a tree structure (fan-out of 1), the garbler generates labels by working backward from the final output gate.

1. For the final gate G' , choose output labels c'_0, c'_1 and solve for its input labels (a'_0, a'_1, b'_0, b'_1) .
2. For a preceding gate G whose output feeds into the first input wire of G' , its output labels are determined by G' 's requirements: $c_0 = a'_0$ and $c_1 = a'_1$.
3. Solve for gate G 's input labels (a_0, a_1, b_0, b_1) using these newly defined c_0, c_1 .
4. This process is repeated backward through the circuit. Since each gate feeds into exactly one subsequent gate, the output labels for every gate are uniquely determined.

2.2 Limitation of the Base Scheme: Fan-out > 1

The backward-pass setup fails for general circuits where a wire's fan-out is greater than one. Consider a gate G 's output wire feeding into both gate G' (requiring input label a'_k) and gate G'' (requiring input label b''_k). The labels a'_k and b''_k are determined independently by the structures of G' and G'' respectively, meaning in general $a'_k \neq b''_k$. Gate G , however, can only produce a single output label c_k . This creates an impossible constraint where c_k must equal both a'_k and b''_k .

3 Static Fan-out Handling with Adaptor Elements

To handle fan-out in general circuits, we introduce static multiplicative "Adaptor Elements." If an output wire W_y (with labels $\ell_{y,0}, \ell_{y,1}$) feeds an input wire W_{xi} that requires different labels, the garbler pre-computes and publishes a static factor $T_{i,k}$:

$$\ell_{xi,k} \equiv \ell_{y,k} \cdot T_{i,k} \pmod{N}$$

The garbler, knowing all base labels during setup, computes this factor as $T_{i,k} \equiv \ell_{xi,k} \cdot (\ell_{y,k})^{-1} \pmod{N}$. These adaptors become part of the public circuit parameters.

4 Reblinding

To reblind the circuit, one can raise the input labels to a secret exponent. The adaptor elements must also be reblinded. For k rounds of reblinding, the garbler publishes pairwise coprime public exponents u_1, \dots, u_k and a secret-derived value $s = \prod_i u_i^{-1} \pmod{\phi(N)}$. The garbler then publishes the reblinded adaptor points $T_{i,k}^s$.

This allows the evaluator to non-interactively compute any singly rebled adaptor point:

$$T_{i,k}^{\frac{1}{u_i}} = (T_{i,k}^s)^{\prod_{j \neq i} u_j}$$

The evaluator can also recover the plaintext $T_{i,k}$ by raising $T_{i,k}^s$ to the power of $\prod_i u_i$.

5 Verifiability and Circuit Correctness

The evaluator can verify the correctness of the garbled circuit’s structure by checking each gate in plaintext. Consequently, the garbler only needs to prove in zero-knowledge that the circuit’s inputs and outputs (which are committed to) were rebled correctly. Thus, the proving complexity amounts to proving in zero-knowledge about 2400 exponentiations with small exponents.

6 Communication Complexity and Onchain Footprint

The primary communication cost is the off-chain transfer of the garbled circuit. A SNARK verifier circuit (e.g., Groth16) may have ~ 5 billion gates. With an average fan-out of 2-4 and a 256-byte RSA modulus, the adaptor elements dominate the circuit size. For each fan-out connection, two adaptors are needed (for logic 0 and 1).

- **Off-chain size:**

$$5 \cdot 10^9 \text{ gates} \cdot 2 \frac{\text{fan-out}}{\text{gate}} \cdot 2 \frac{\text{elements}}{\text{fan-out}} \cdot 256 \frac{\text{bytes}}{\text{element}} \approx 5 \text{ TB}$$

Although sharing the circuit takes about 1.8 days with a 250 Mbps upload speed, this is a one-time setup cost.

- **On-chain ‘assertTx’ size:** For a proof with 128 bytes of private inputs and 20 bytes of public inputs, the garbler must commit to the input labels. This is optimized by publishing encrypted labels during setup and revealing 16-byte decryption keys on-chain.

$$148 \text{ bytes} \cdot 8 \frac{\text{wires}}{\text{byte}} \cdot \left(2 \frac{\text{labels}}{\text{wire}} \cdot 16 \frac{\text{bytes}}{\text{label}} + 1 \frac{\text{dec.key}}{\text{wire}} \cdot 16 \frac{\text{bytes}}{\text{dec.key}} \right) \approx 56 \text{ kB}$$

- **On-chain ‘disproveTx’ size:** This transaction is minimal. It simply reveals the hash of the output label for ‘0’, signifying that the SNARK proof was invalid.

7 Conclusion

BitVM3 significantly advances Bitcoin’s contracting capabilities by using an RSA-based garbled circuit to move SNARK verification off-chain. This approach reduces the on-chain footprint to a 56 kB assertTx and a 200-byte disproveTx, but requires a multi-terabyte off-chain data setup. While this trade-off enables much more capital efficient trust-minimized bridges for second layers like rollups and sidechains, future work must focus on reducing the off-chain data burden. Ultimately, BitVM3 demonstrates a viable path toward using Bitcoin as a secure settlement layer for arbitrarily complex computations.