Zero-Knowledge Proof Schemes for Lightweight IoT Devices in Permissioned Blockchain Networks

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Agenda

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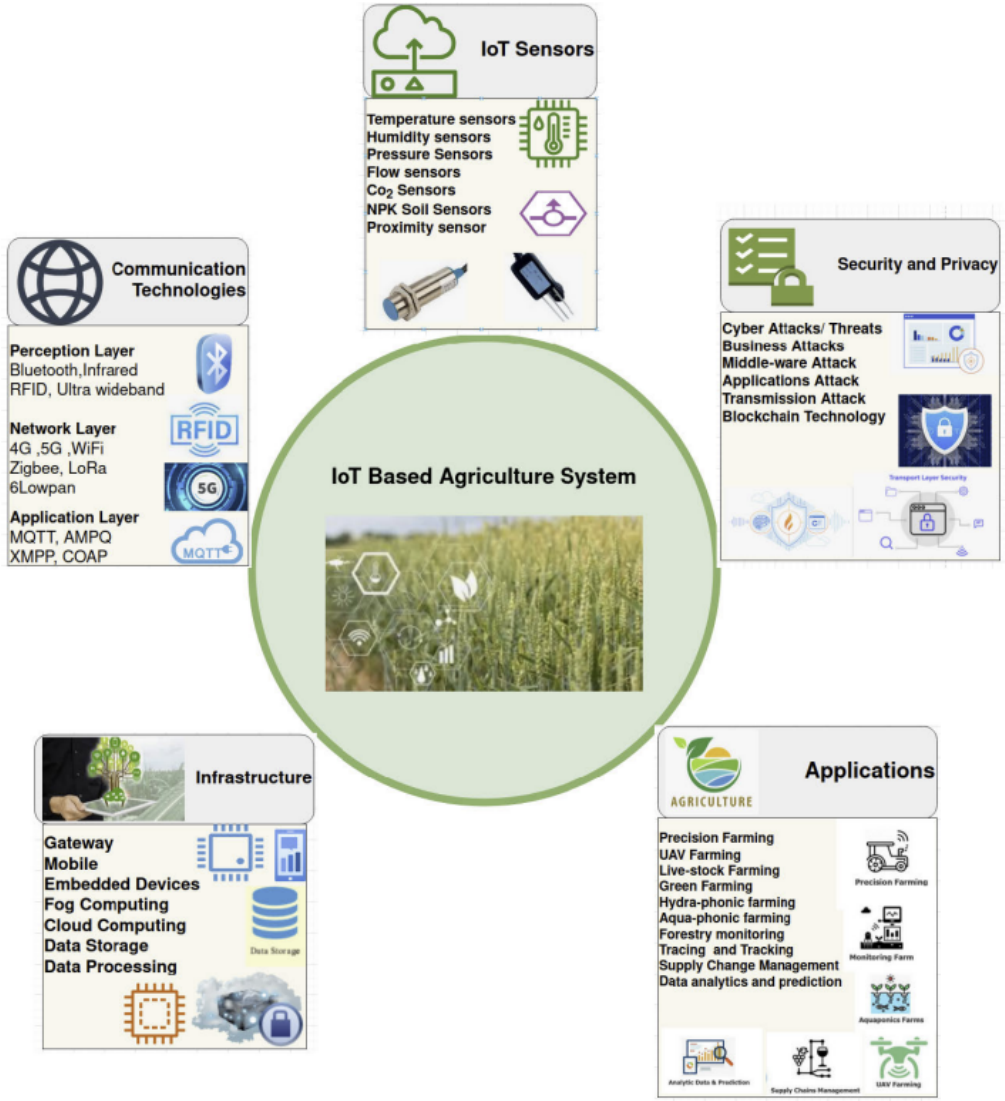
IoT Security Challenges

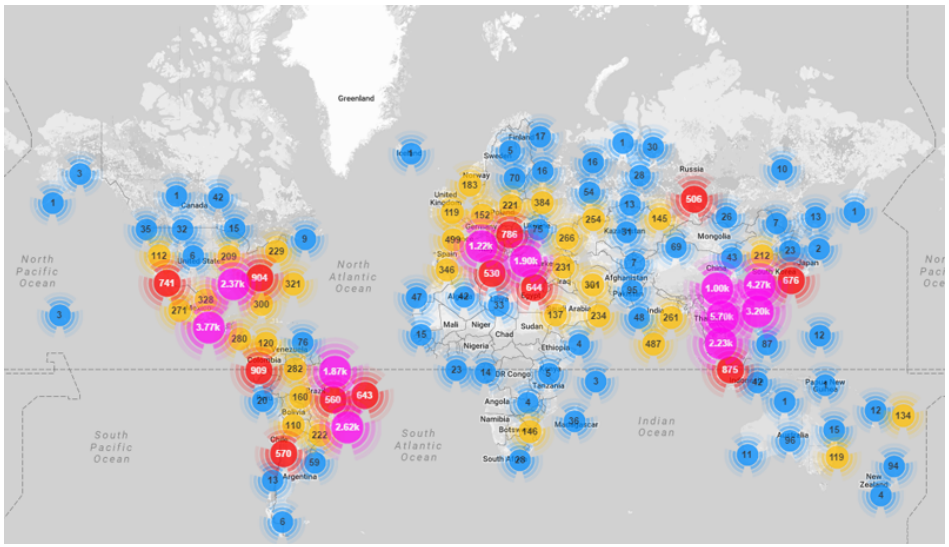
- The Internet of Things (IoT) is massive, forecast of over **75 billion** connected devices by 2025 (nccoe.nist.gov).
- Traditional methods often prove inadequate, especially as many devices are deployed in uncontrolled environments and can be **physically or remotely attacked**.
- A main issue is **poor/absent authentication** in IoT systems.



Taxonomy IoT based agriculture system.

Case Study: Mirai Botnet (2016)

- The Mirai botnet attack was a massive DDoS attack that affected millions of devices connected to IoT; simply by exploiting default passwords and trivial credentials (usenix.org).
- Exposed how easily malicious actors can hijack poorly secured "smart" cameras, routers, and sensors, using them in coordinated cyber-attacks.
- Underscored that conventional authentication (factory-set passwords/static keys) is not robust enough for IoT's scale.

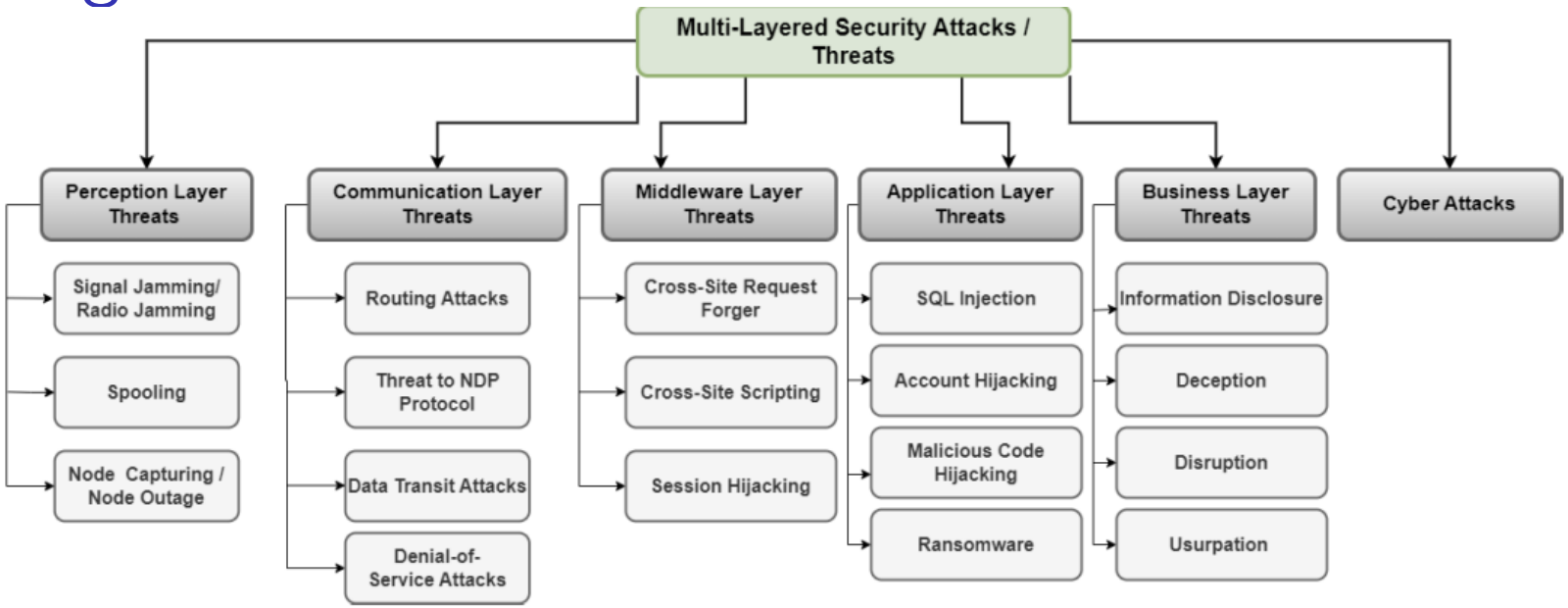


Attack Vector

Country	% of Mirai botnet IPs
Vietnam	12.8%
Brazil	11.8%
United States	10.9%
China	8.8%
Mexico	8.4%
South Korea	6.2%
Taiwan	4.9%
Russia	4.0%
Romania	2.3%
Colombia	1.5%

Device Hijacking

Challenges in Conventional IoT Authentication



Taxonomy of multi-layered security and privacy concerns in IoT

- Many IoT devices lack user interfaces for updating credentials.
- Centralized auth servers become points of failure in distributed ecosystems.
- Heavyweight cryptographic handshakes (e.g., full TLS with certificate verification) are impractical for resource-constrained devices.
- Manufacturers often resort to simpler, yet less secure, schemes to reduce computational load.
- **Conclusion:** IoT growth has outpaced current security measures
- **Solution:** A new authentication paradigms for IoT is needed

Zero-Knowledge Proofs (ZKPs)

Core Idea:

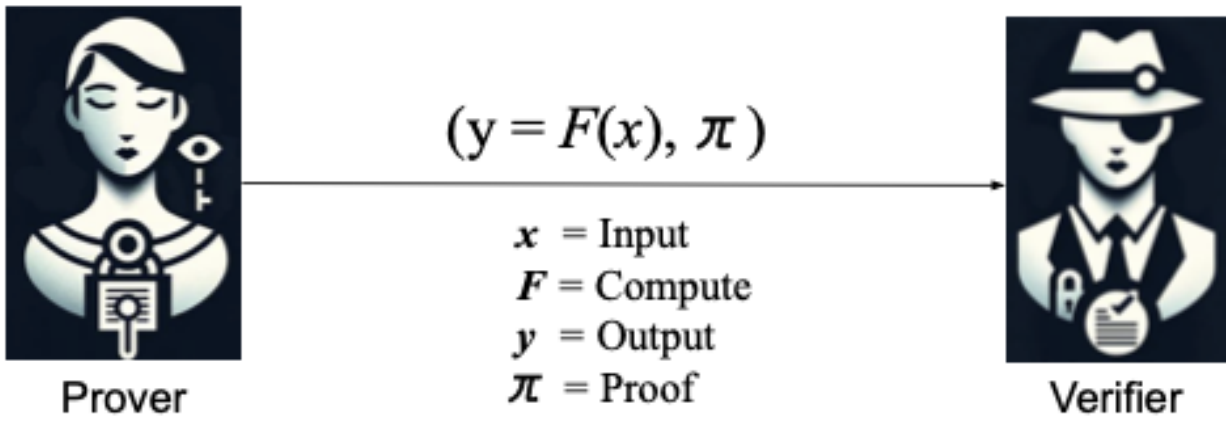
- Prover convinces verifier of a truth statement's *without* revealing secrets
- A device can prove private-key possession *without* disclosing it

Advantages:

- Immunity to replay attacks (since cannot reusable secrets)
- Privacy-preserving (no raw data or ID dispose)
- Non-interactive proofs reduce overhead

Result:

- Trust established *mathematically*
- Facilitates large-scale devices deployments



Key components of zero-knowledge proofs

ZKP Fundamentals: Interactive vs. Non-Interactive

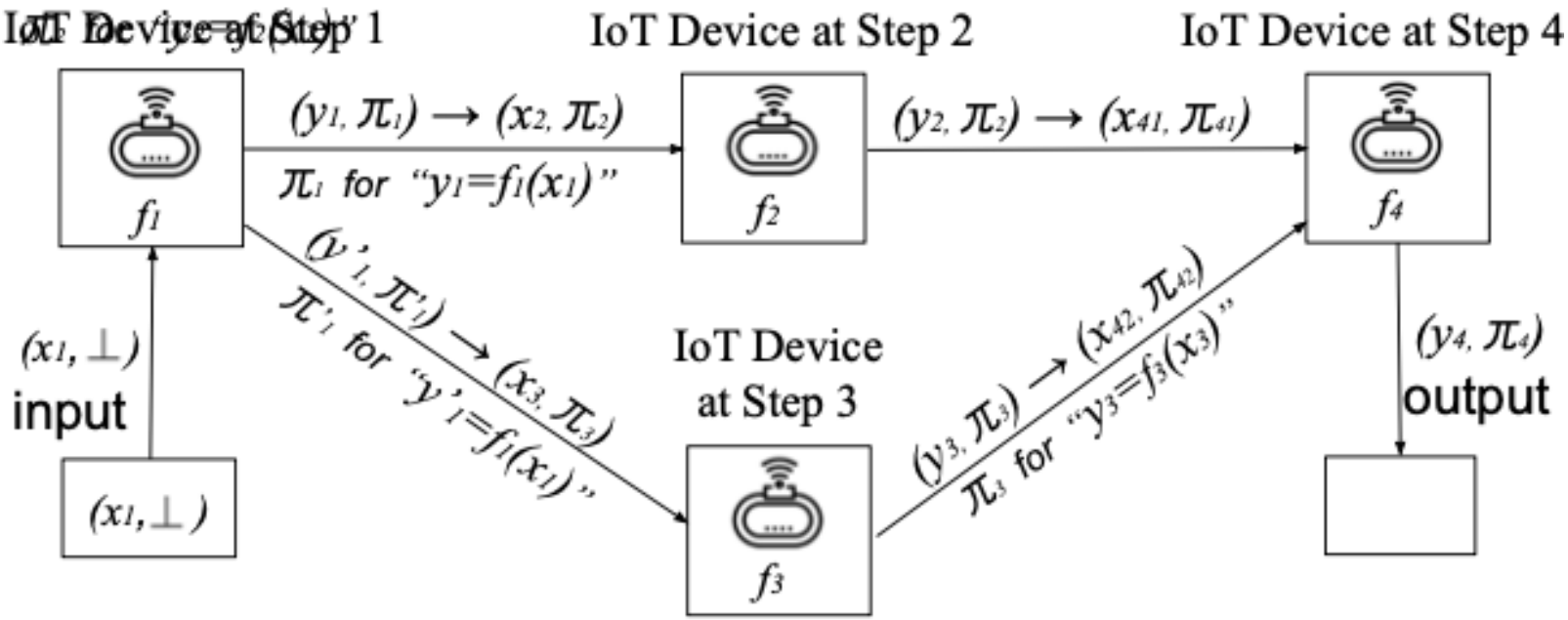
Interactive to Non-Interactive

- Early ZKPs were **interactive**: Prover & Verifier exchanged multiple messages.
- The **Fiat–Shamir** heuristic converts multi-round proofs into a single-message scheme.
- This is crucial for IoT with constrained bandwidth or sporadic connectivity (reduces round trips).

In IoT, non-interactive ZKPs (NIZKs) help reduce communication overhead, making them more practical for large-scale device authentication.

Type	**Rounds**	**Comm Overhead**	**IoT Fit**
Interactive	Multi	Higher	Limited
Non-Interactive	Single	Lower	Preferred

ZKPs as a IoT Authentication Solution



A sample IoT devices setup with ZKP

Why choosing ZKPs as a new solution to IoT authentication?

- IoT device can proves "X" *without* revealing secrets.
- Keeps sensitive data hidden.
- Minimizes communication overhead.
- Math-based proof replaces shared secrets, reducing the attack surface.

Real-World Applications

Military & Defense IoT:

- Sensors prove authenticity without revealing location

Critical Infrastructure:

- Smart meters: privacy-preserving billing proofs on blockchain

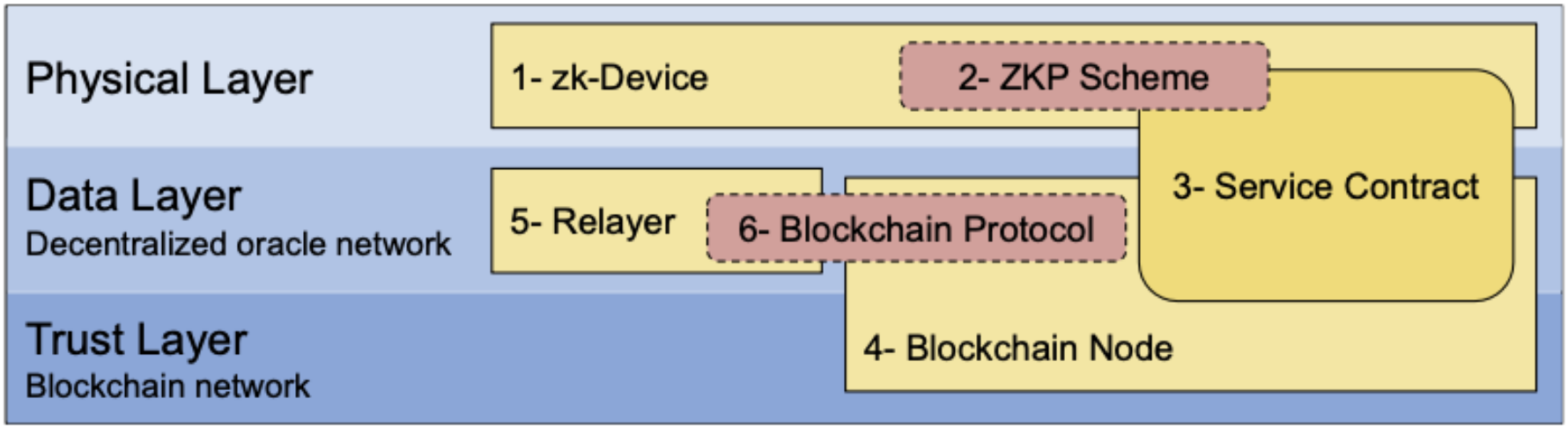
Supply Chains:

- Prove product origin/compliance w/o disclosing sensitive info

Blockchain in zk-IoT

	Permissionless	**Permissioned**
Membership	Open to public	Restricted
Throughput	Low (e.g., 7–30 TPS)	Higher (100+ TPS)
Fees	Usually required (gas)	Often zero or internal
ZKPs	More privacy & small proofs	Selective disclosure

Main Differences between Permissionless Blockchain vs. Permissioned



The main components of the zk-IoT framework

zk-IoT Communication on Blockchain Layers

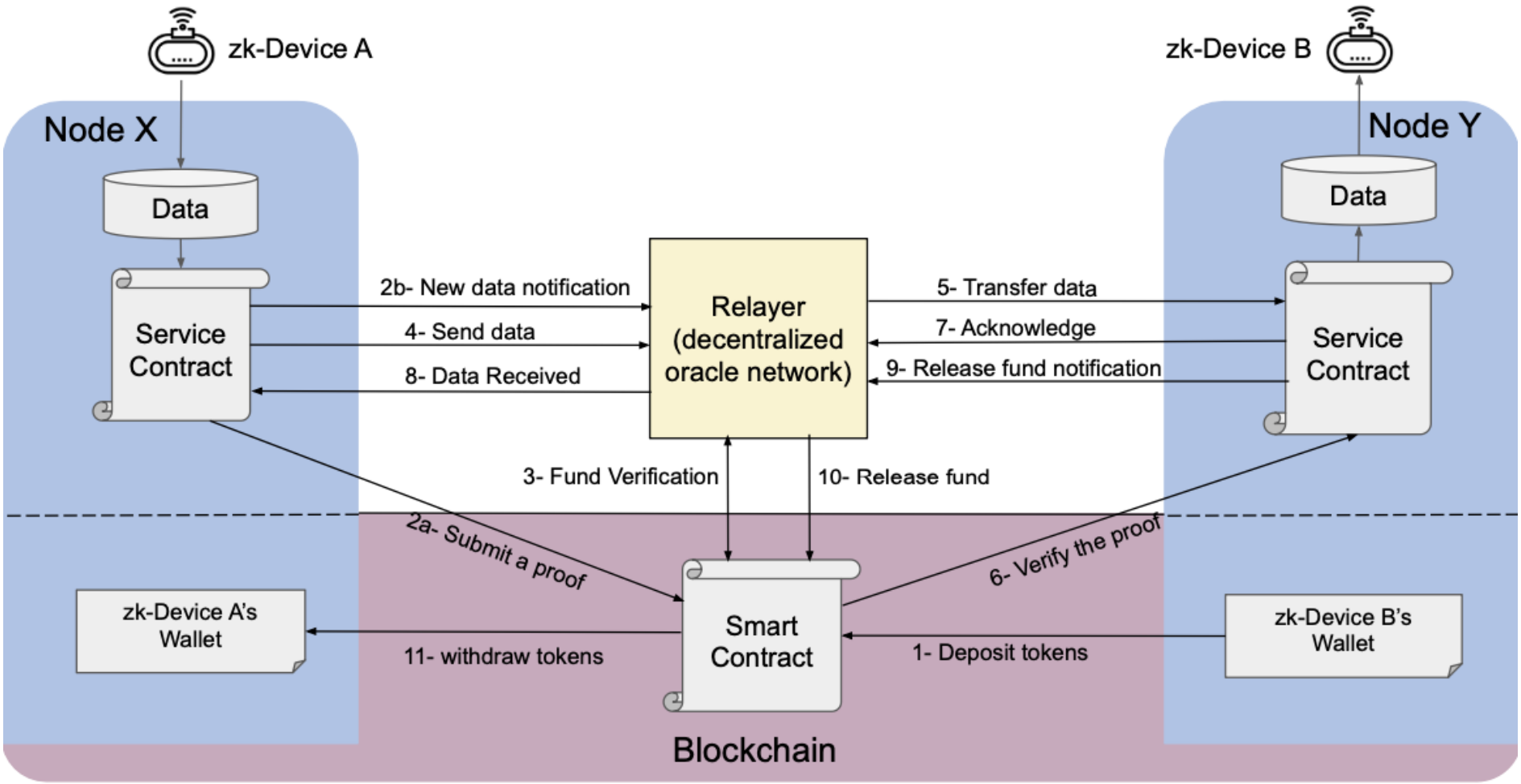


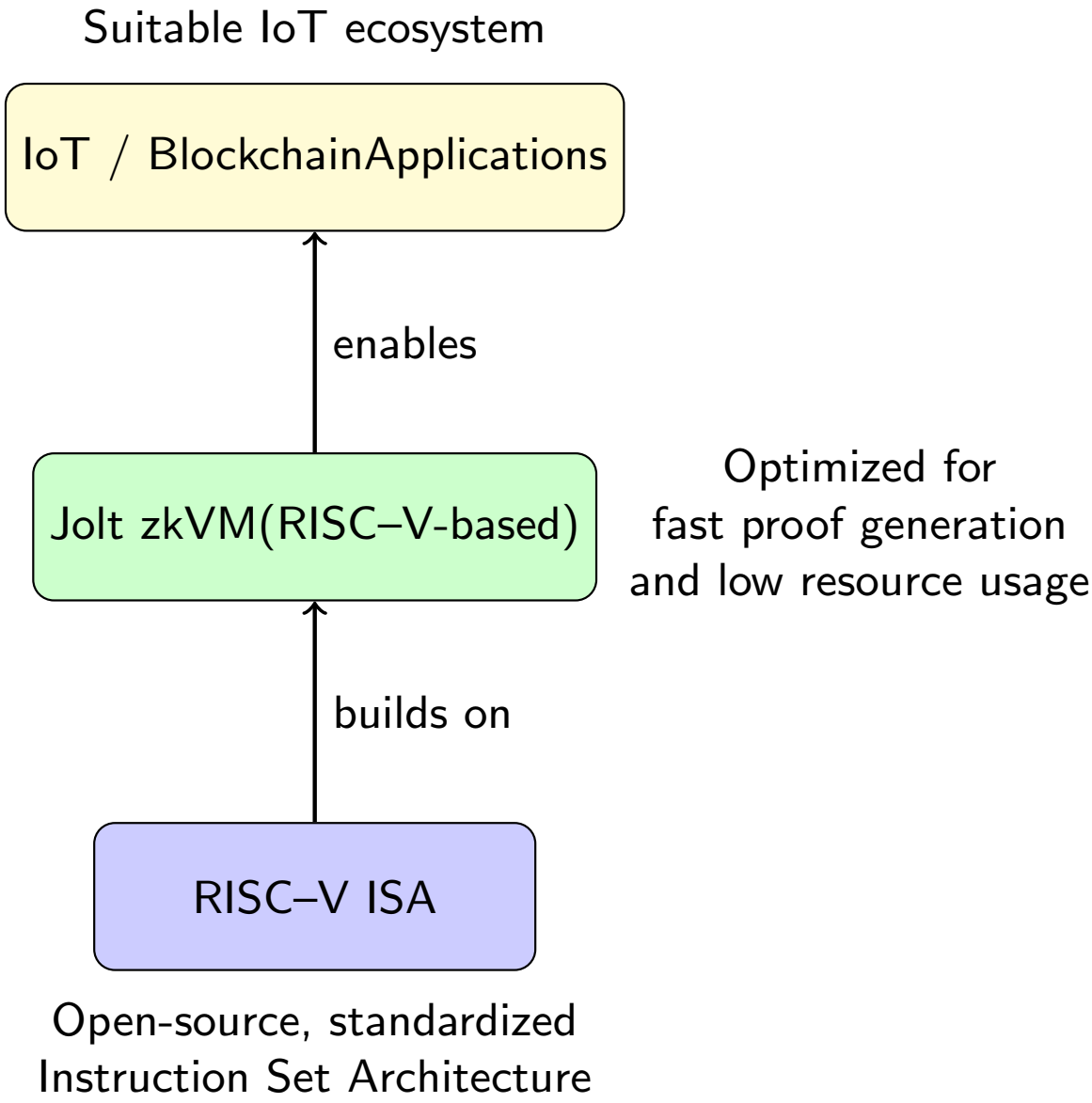
Illustration of zk-IoT communication across blockchain layers

ZKP Families & Comparative Metrics

Approach	Proof Size	Prover Cost	Verifier Cost	Setup
zk-SNARKs	$<$1 KB	High (heavy on RAM)	Very fast	Trusted
zk-STARKs	Tens of KB	High (parallelizable; memory intensive)	Slower	None; post-quantum
Bulletproofs	$\sim$2 KB	Moderate (sec on MCUs)	Moderate	None
Jolt zkVM	$<$1–few KB	Very fast (2–5$\times$ faster than other zkVM)	Extremely fast	Trusted

- SNARKs: Ideal for low-bandwidth; often requires outsourced proving
- STARKs: no trusted setup, but bigger proofs, suited for complex computations.
- Bulletproofs: good for smaller statements (e.g., range proofs).
- **Jolt zkVM: Jolt zkVM builds on SNARK principles; its setup is streamlined for R1SC-V applications. Therefore, fast, scalable and suitable for IoT system**

Jolt zkVM and R1SC-V Relationship



Challenges in Applying ZKPs to IoT

Computational Efficiency:

- Existing ZKP schemes are computationally heavy for IoT devices.
- Involve intensive math (modular arithmetic, FFTs, large transcript hashing).

Scalability:

- IoT networks can involve thousands of devices sending frequent proofs.
- Verification and network overhead can become bottlenecks.
- Distributed proof generation, batched/aggregated proofs, and recursive ZKPs is not widely investigate and everyday-applied

Blockchain Integration Challenges:

- Verification is limited (e.g., high gas costs on Ethereum).
- Storing numerous proofs may bloat the blockchain.
- Trusted setups (for zk-SNARKs) and a lack of standardized interfaces create integration gaps.

Proposed Solution & Main Contributions

Proposed Solution:

- Develop a new lightweight ZKP algorithm built on Jolt zkVM (leveraging RISC-V).

Main Contributions:

- A ZKP algorithm that specifically for IoT devices for small IoT devices.
- (Hopefully) Achievable fast proof generation and verification rate.
- Enhanced scalability for high-frequency IoT authentication.

Thank you for listenting
Q & A