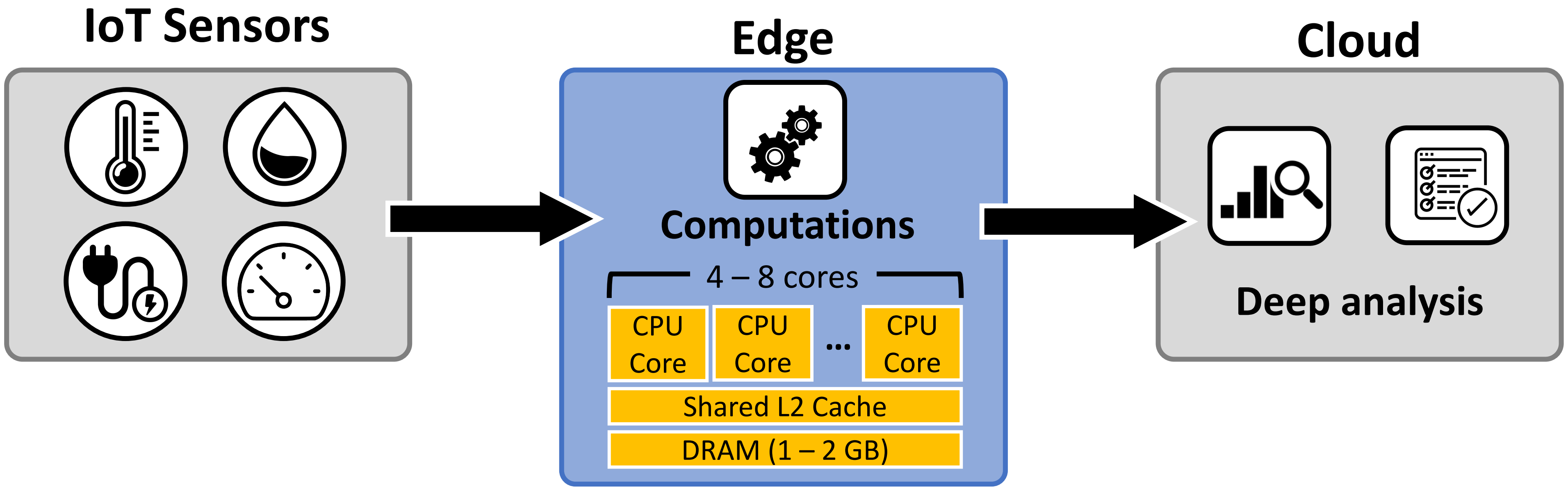
StreamBox-TZ:
Secure Stream Analytics at the Edge with TrustZone

Heejin Park[1], Shuang Zhai[1], Long Lu[2], and Felix Xiaozhu Lin[1]

[1]Purdue ECE, [2]Northeastern University

http://xsel.rocks

Scenario: Edge Processing for IoT



- **Large telemetry data streams come from IoT sensors**
  - 140M samples/day (smart grid), 1-2 TB/day (oil production)
- **Edge processing is emerging**
  - Cleanse and summarize data
- **ARM processor as edge device** – compelling performance at low power

Security Threats on Edge Processing

Edge

Analytics Engine
(Flink, Esper, Spark Streaming, SensorBee)

Libraries
(libc, libstdc++, libssl)

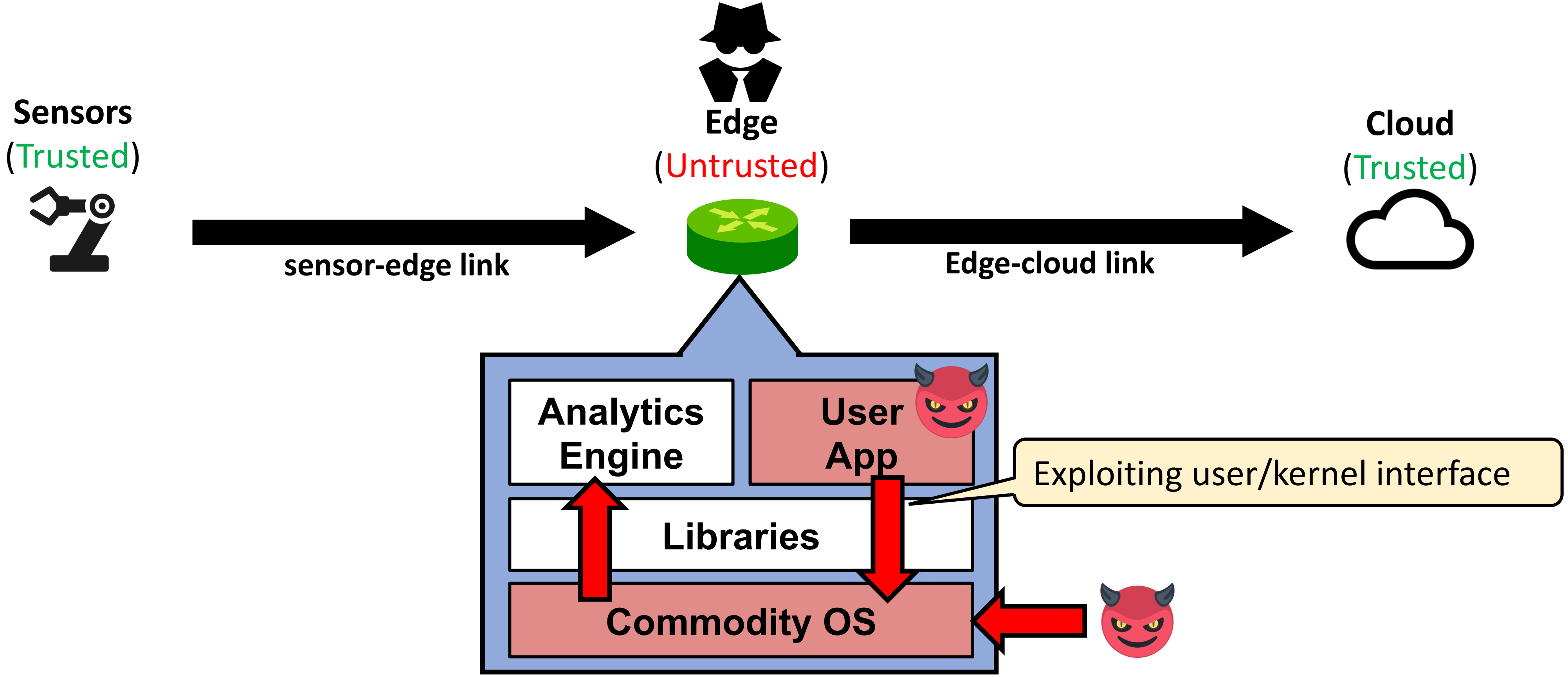
Commodity OS
(Linux / Windows)

Common IoT weaknesses

- Lack of professional supervision
- Weak configuration
- Delayed security updates

- **Wide Attack Surface**
  - Large and complex software stack (engine, libraries, and OS)
- **High-value target**
  - Data aggregated from multiple sources

Threat Model



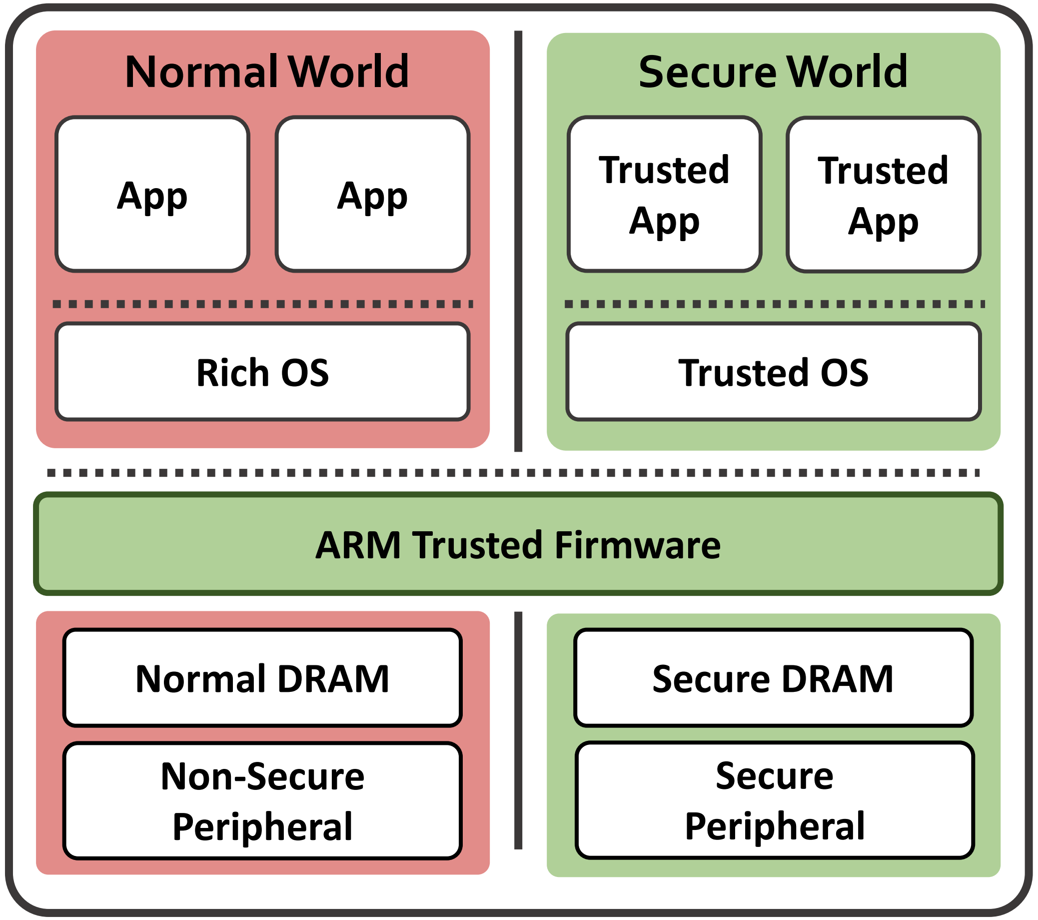
Powerful adversaries – control entire edge OS

Problem Statement

How to securely process large streams of IoT data at the edge?

Approach: Isolate data and its computation within TEE,
shielding them from the remaining edge software stack

Background: ARM TrustZone



- **Security extension for TEE enforcement**
- **Resource partitioning**
  - Normal world and secure world
  - Limited secure world memory
- **Trusted IO**
  - Peripheral is owned by secure world
  - Direct access to secure world

Challenges

Design constraints:

1. Minimal TCB
2. Limited memory in TEE

Challenge 1) What functionalities should be in TEE and behind what interfaces?

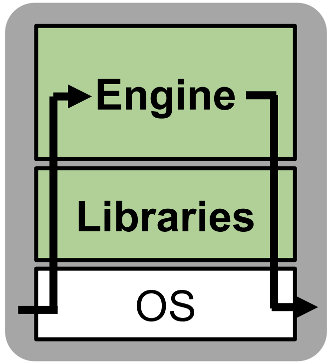
Challenge 2) How to execute stream analytics with high throughput and low delay?

Challenge 3) As untrusted components are in analytics, how to verify the outcome?

Why Are Existing Systems Inadequate?

Engine and its libs in TEE

Haven [OSDI 14], Scone [OSDI 16], Graphene-SGX [ATC17]

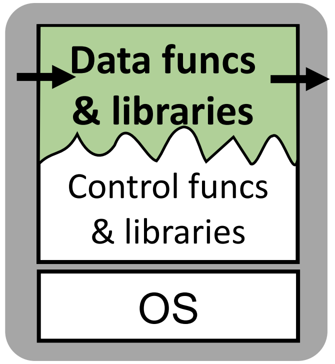


- Large and complex engine
- Potentially vulnerable Libraries

Large TCB

Partitioning as-is

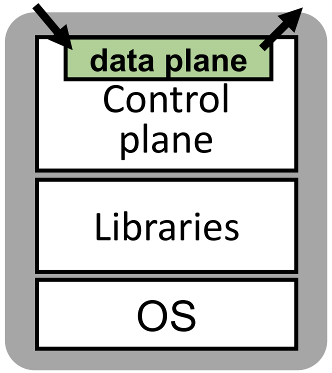
Glamdring [ATC 17], Panoply [NDSS 17]



- Unsuitable for existing engines
- Mismatch TEE's limited memory

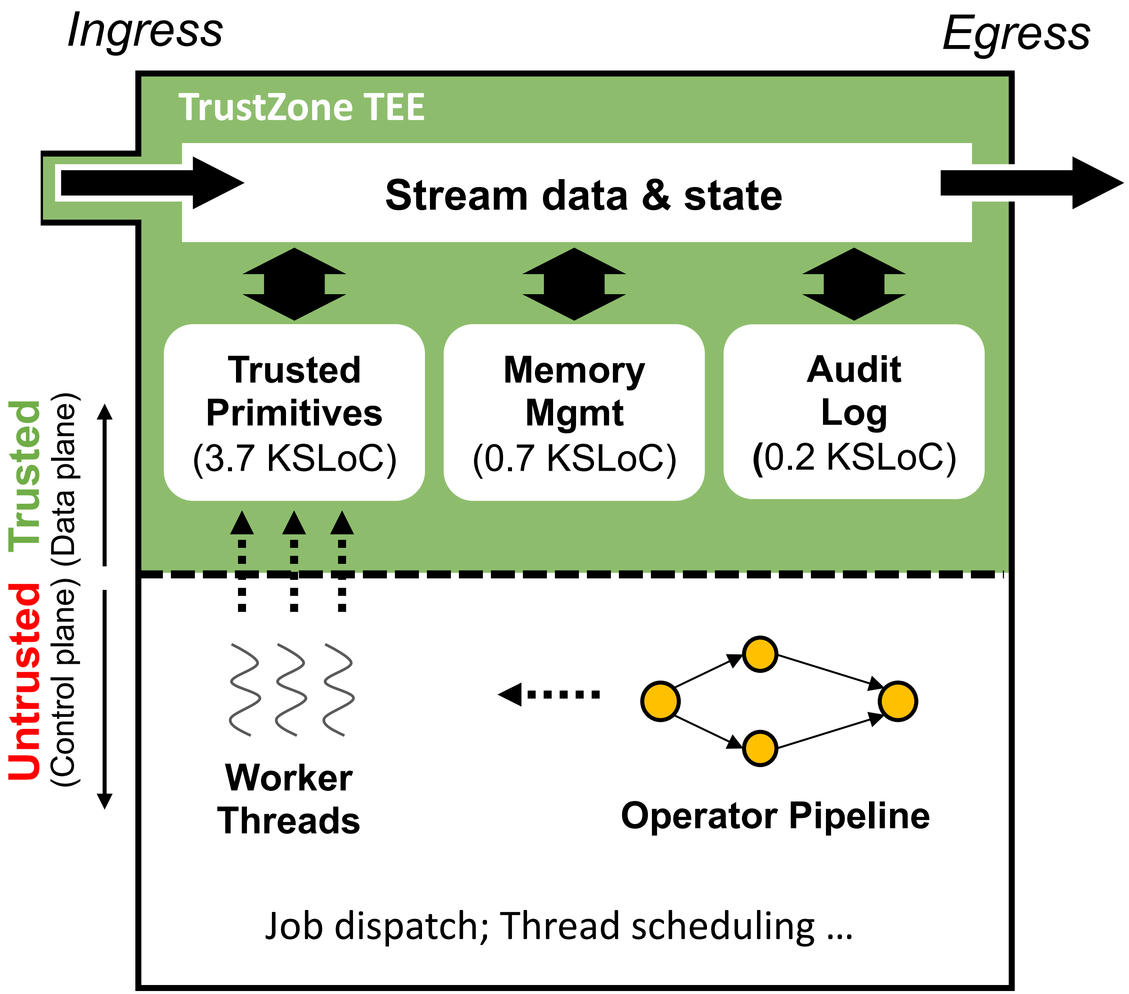
Wide interface
High memory usage

StreamBox-TZ



- How is our design different?
  - Solution 1) Architecting a data plane for protection
  - Solution 2) Optimizing a data plane performance within a TEE
  - Solution 3) Verifying edge analytics execution

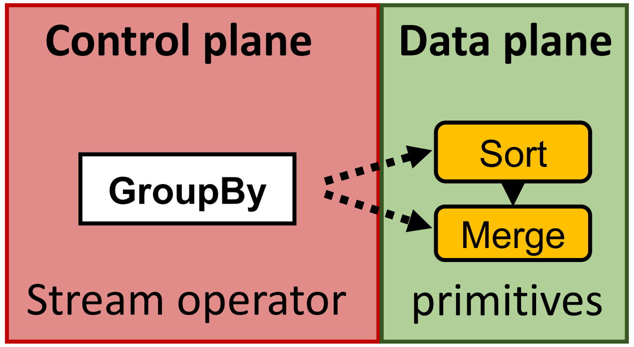
Technique 1: Architecting a Data Plane for Protection



- **Data plane** (trusted)
  - Enclose all the analytics data and its computation
  - Keep low TCB (5K SLoC)
- **Control plane** (untrusted)
  - Contains control functions (e.g. scheduling)
- **Narrow, shared nothing interface**
  - Only 4 entry functions
    (init; clean; entry point; debug)

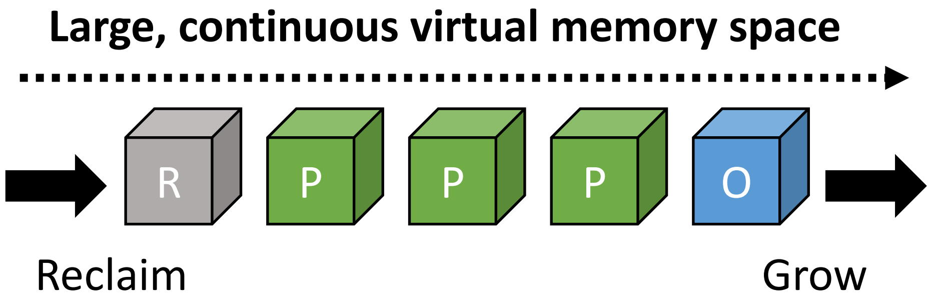
Technique 2: Optimization – Parallel Execution In a TEE

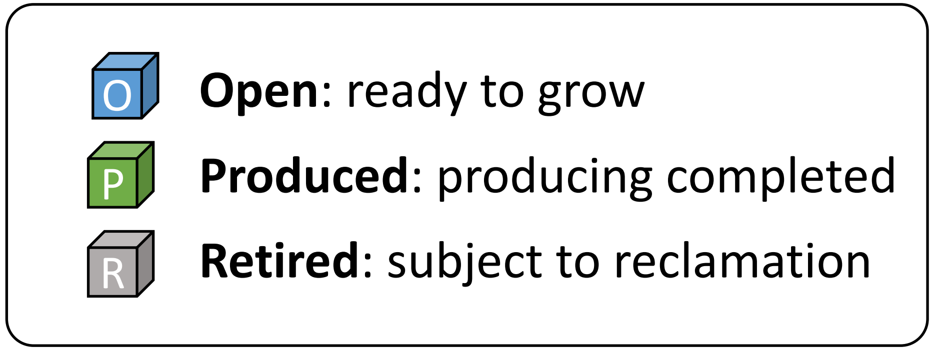
Popular Stream Operators	Trusted Primitives
`GroupByKey, Windowing, AvgPerKey, Distinct, SumByKey, AggregateByKey, SortByKey, TopKPerKey, CountByKey, CountByWindow, Filter, MedianByKey, …`	`Sort, Merge, Segment, SumCnt, TopK, Concat, Join, Count, Sum, Unique, FilterBand, Median, …`



- **Trusted Primitives**: low-level stream algorithms
  - Building stream operators
  - Single threaded, stateless and oblivious to sync.
  - Sharing cache-coherent memory space in TEE → simplify data sharing/avoid copy cost

Technique 2: Optimization – Memory Mngt in a TEE

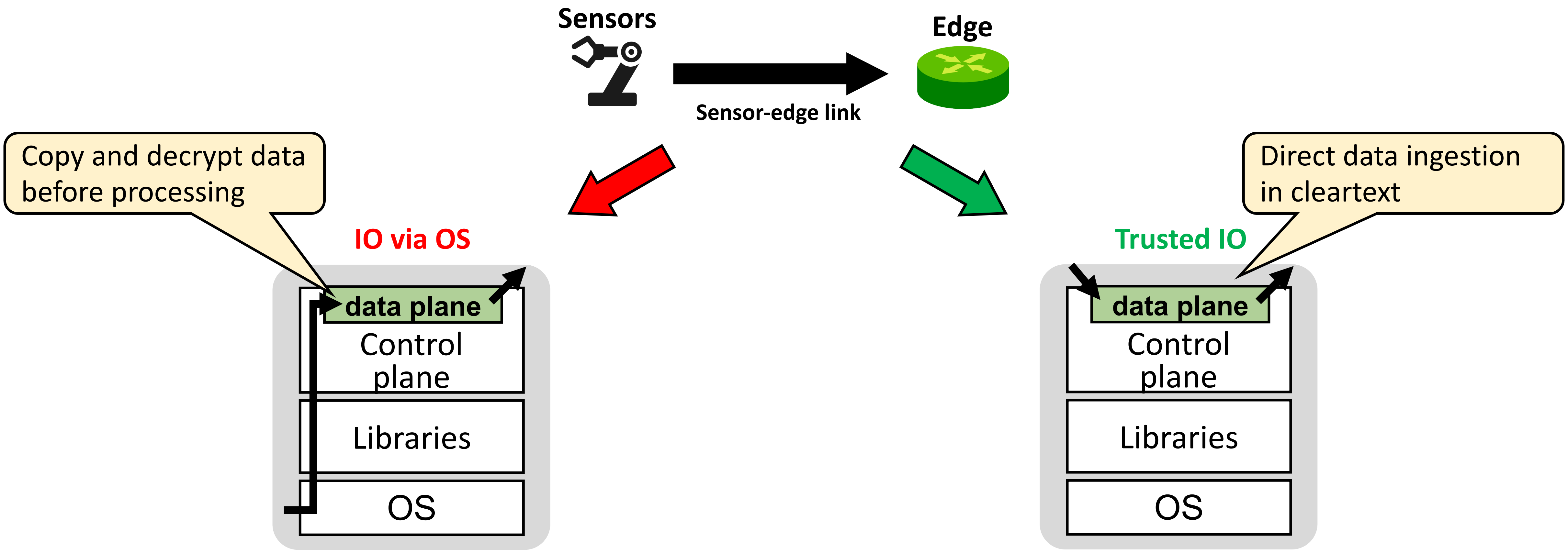




- **Unbounded array**
  - Data container for trusted primitives & operator states
  - In-place growing backed by on-demand paging inside TEE

- **Space efficient** – append-only buffer in a contiguous memory region
- **No relocation overhead** – large, dedicated virtual memory regions
- **Lightweight** – 0.7 KSLoC (9x fewer than malloc, 20x fewer than jemalloc)

Technique 2: Optimization – Low Ingestion by Trusted IO



- Source-edge link – via OS
  - Copy- and crypto-overhead
- Source-edge link – via trusted IO
  - Direct ingestion into TEE, bypassing OS

Technique 3: Verifying Edge Analytics Execution

Data plane generate audit records

Symbolic replay

- Tracking the origin of result (data lineage) is insufficient – lack of steam semantics
- **Audit record**: generated by data plane when invoked
  - Data flow among primitives with stream model-awareness (e.g. window, watermark)
- **Cloud verifier**: replays all ingestion records
  - **Correctness** – all ingested data is processed correctly
  - **Freshness** – the pipeline has low output delays

Implementation & Evaluation

SoC	HiSilicon Kirin 620, TDP 36W	**CPU**	8x ARM Cortex-A53@1.2 GHz
Mem	2GB LPDDR3@800 MHz	**OS**	Normal: Debian 8 (Linux 4.4) Secure: OP-TEE 2.3

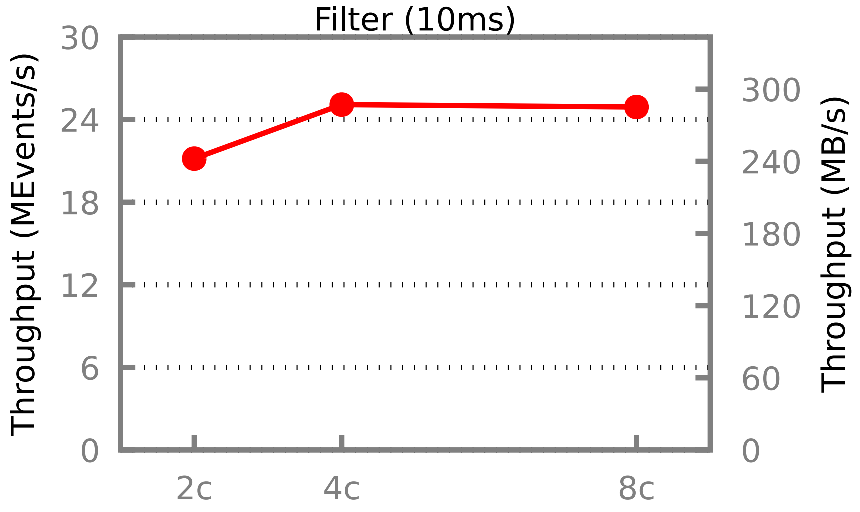
- Implementation
  - Control plane (written by C++, 12.4K SLoC newly added)
    - Reuse and modify code from StreamBox [ATC 17]
  - Data plane (written by C, 5K SLoC)
    - Newly implement form scratch

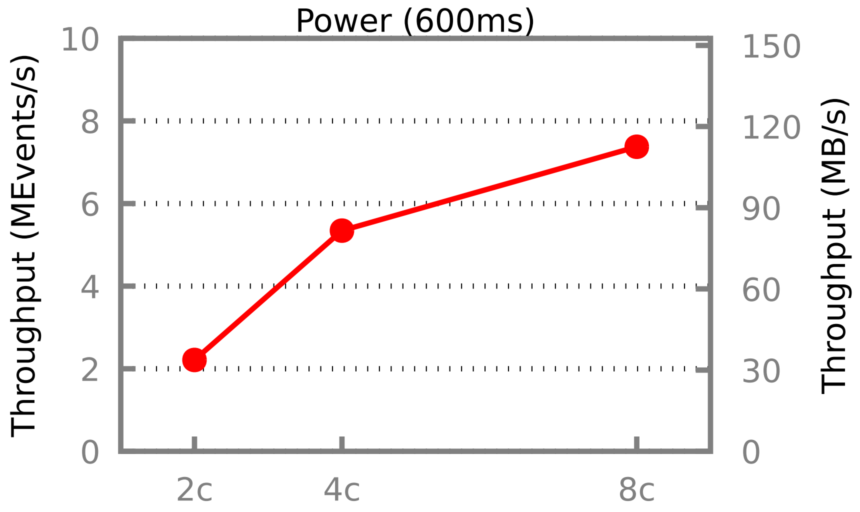
- 6 benchmarks of processing sensor data streams
  - Filter, Power, WinSum, TopK, Distinct, and join

- 4 different versions of StreamBox-TZ

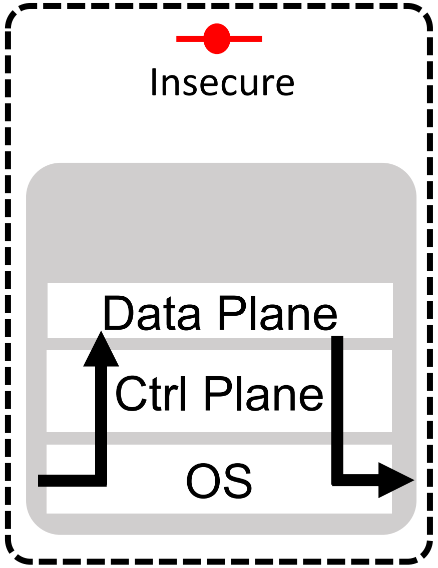
Security Overhead: what is the cost of isolation?

Insecure: Running in Normal World

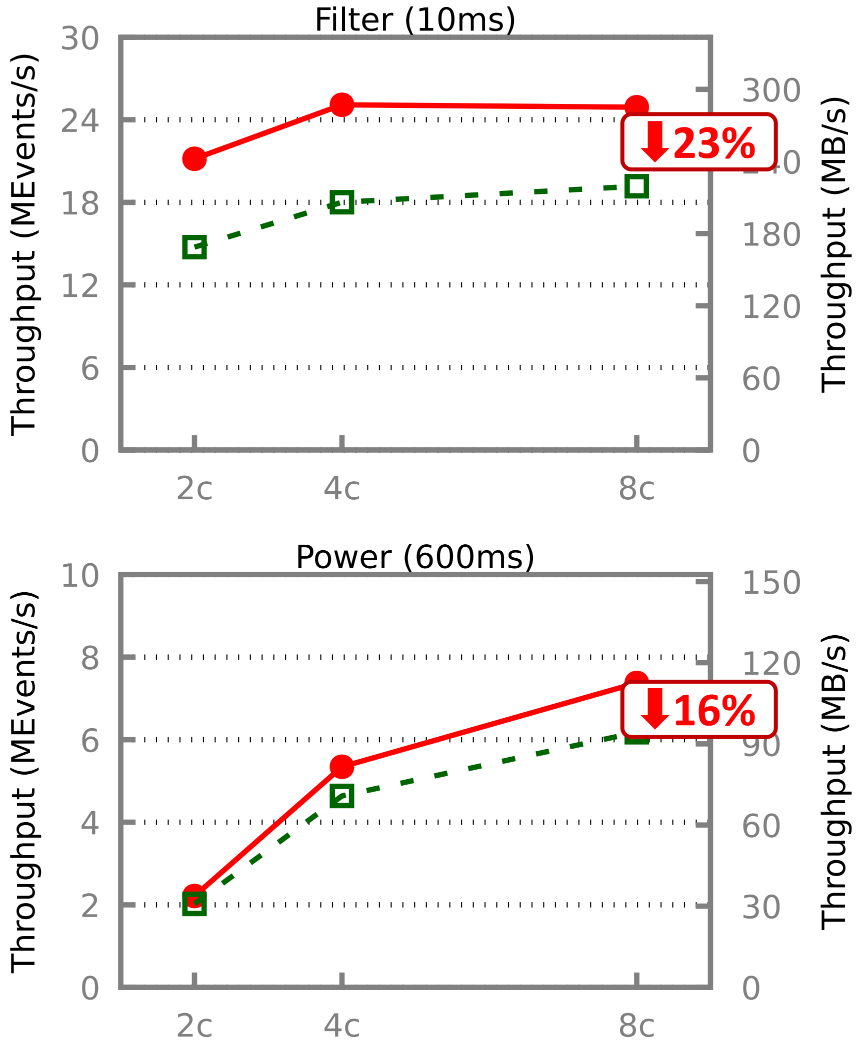


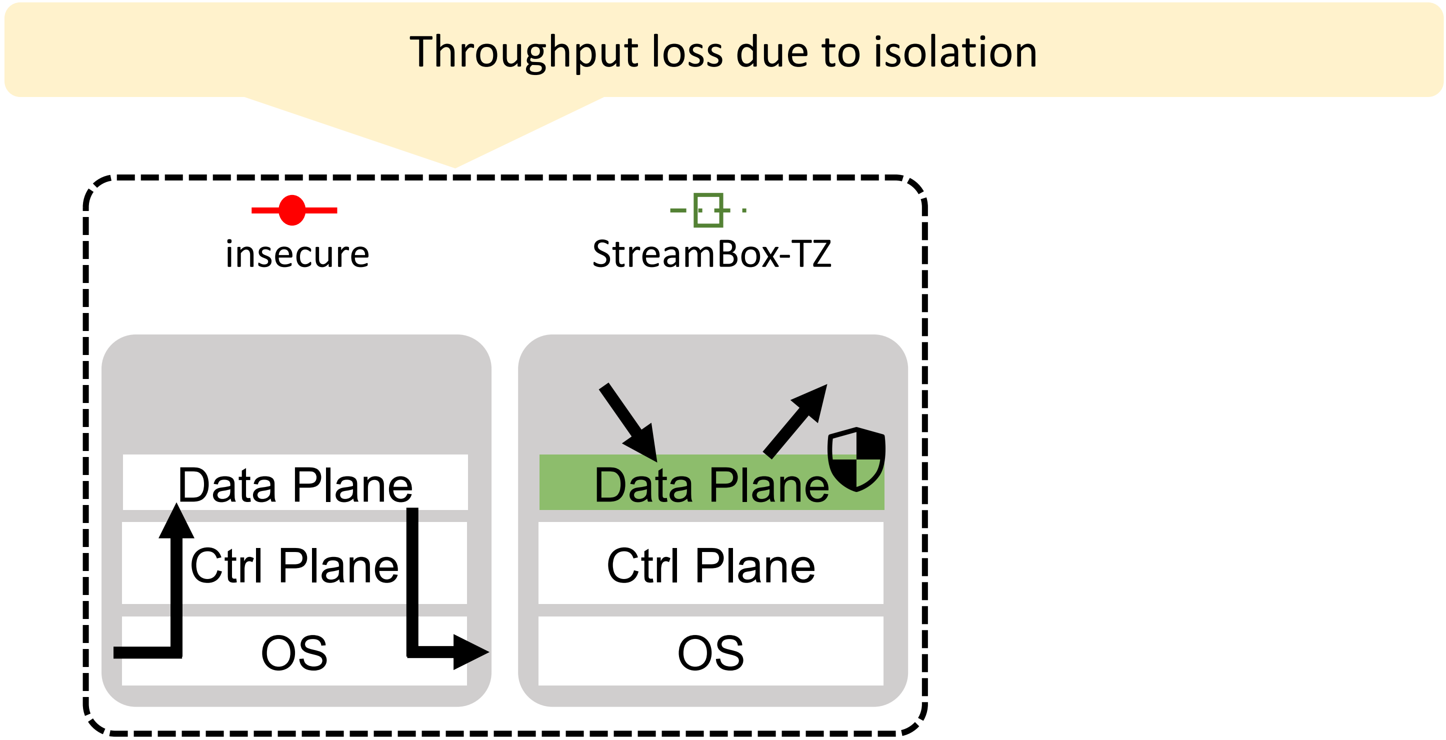


Native performance of StreamBox-TZ running in **normal world**



Modest Security Overhead from Isolation

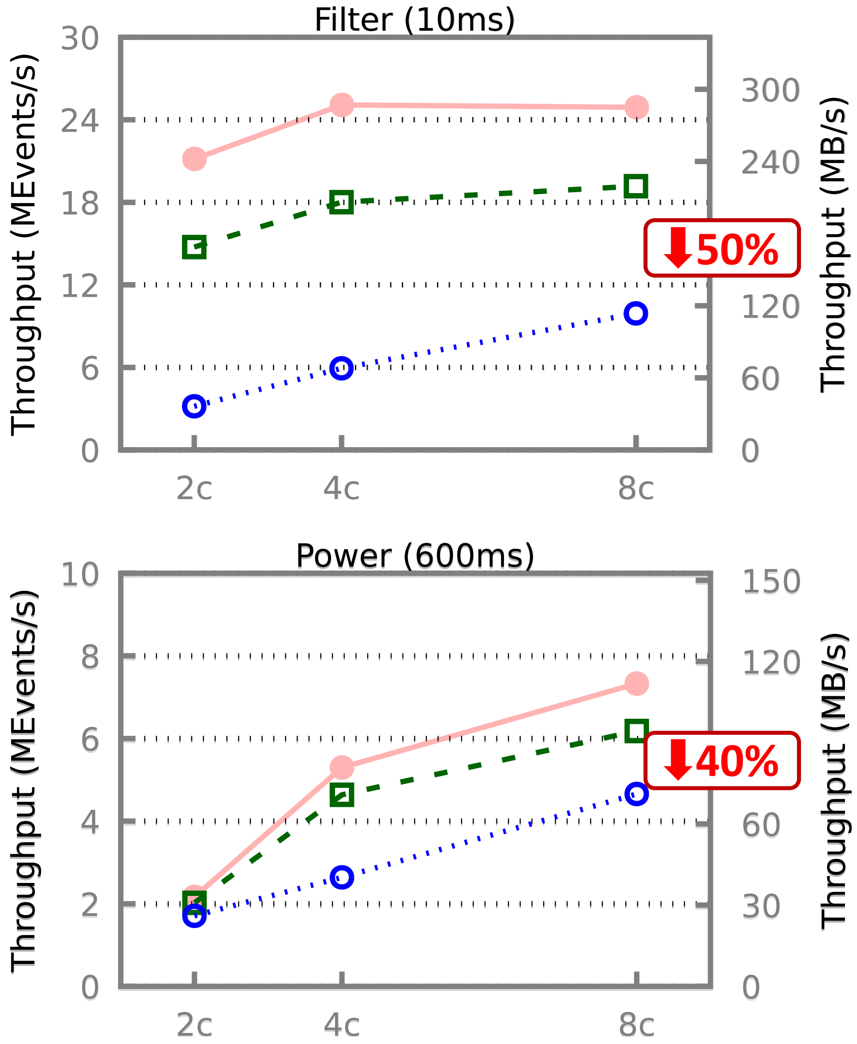




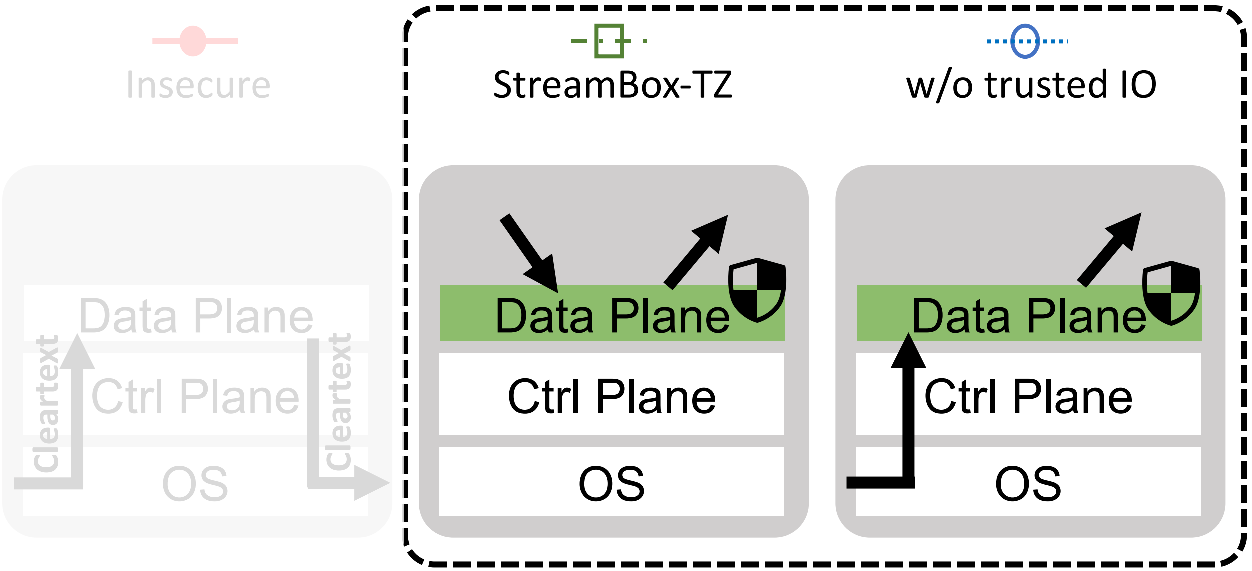
- Modest security overhead (less than 25%)

What is the impact of Trusted IO?

Impact of w/o Trusted IO



Performance impact from **direct data (trusted IO)** ingesting into TEE



- 40 ~ 50% throughput loss without trusted IO
  - Data copy-, crypto-overhead

Conclusion

- **StreamBox-TZ**: secure stream analytics engine at the edge
  - Exploit ARM TrustZone as TEE
  - Data-intensive, parallel computations on minimal TCB
- Compelling performance with strong security
  - Architecting data plane for protection
  - Optimizing data plane performance within a TEE
  - Verifying edge analytics execution

Questions?