Funded by DFG

Technische Universität Braunschweig

Precursor: A Fast, Client-Centric and Trusted Key-Value Store using Intel SGX and RDMA

Middleware 2021

Ines Messadi, Shiva Neumann, Nico Weichbrodt, Lennart Almstedt, Mohammad Mahhouk, and Rüdiger Kapitza

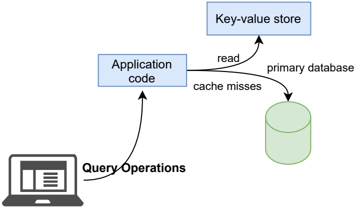
TU Braunschweig, Germany

Key-value Stores in the Cloud

- Key-value stores are core of large-scale services
  → **Low latency** & **high request rate** are key

- When outsourced to the cloud
  - User data is exposed to malicious attacks

  → Concerns about **privacy** & **integrity**

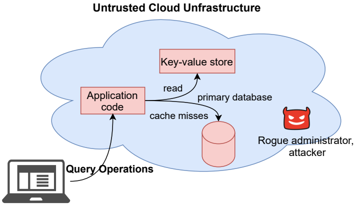


Key-value Stores in the Cloud

- Key-value stores are core of large-scale services
  → **Low latency** & **high request rate** are key

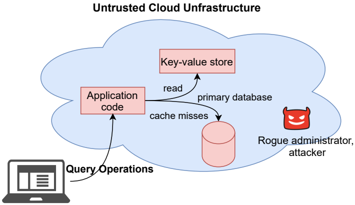
- When outsourced to the cloud
  - User data is exposed to malicious attacks

  → Concerns about **privacy** & **integrity**



Key-value Stores in the Cloud

- Key-value stores are core of large-scale services
  $\rightarrow$ **Low latency** & **high request rate** are key



- When outsourced to the cloud
  - User data is exposed to malicious attacks

  $\rightarrow$ Concerns about **privacy** & **integrity**

Improvements with trusted execution environments such as **Intel Software Guard Extensions (Intel SGX)**

Research vs. Industry

- Industry
  - REDIS, MEMCACHED..

→ Lack of basic security guarantees, e.g plaintext key-value items

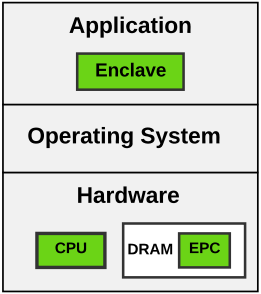
- Research
  - Concerto [Arasu et al., SIGMOD'17], ShieldStore [Kim et al., Eurosys'19]

→ Secure but intensive computations

How to reduce the overhead of intensive computations?

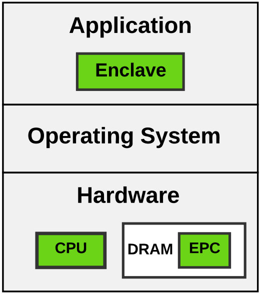
Intel SGX Model

- Extension of the x86 instruction set
- Applications have secure compartments
  $\rightarrow$ **Enclave**
- Code & data reside in **Enclave Page Cache (EPC)**
- Confidentiality and integrity protected
- Restriction of **systems calls and I/O operations**



Intel SGX Model

- Extension of the x86 instruction set
- Applications have secure compartments
  $\rightarrow$ **Enclave**
- Code & data reside in **Enclave Page Cache (EPC)**
- Confidentiality and integrity protected
- Restriction of **systems calls and I/O operations**



- SGX-based key-value stores
  - Library OS solutions: GRAPHENE-SGX [Tsai et al., ATC'17], ..
  - Tailored solutions: SHIELDSTORE [Kim et al., Eurosys'19], SPEICHER [Bailleu et al., FAST'19]

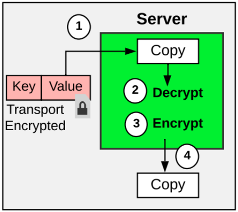
Intel SGX Architectural Limitations

1. Limited EPC memory
   - Overhead up to $\times$ 1000 (SCONE [Arnautov et al., OSDI'16])

   $\rightarrow$ Cannot protect the full state using the EPC memory

2. System call restriction & enclave transitions
   $\rightarrow$ Performance loss

3. DMA directly into the enclave are not allowed
   $\rightarrow$ Large copy overhead



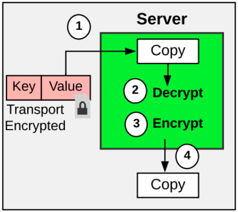
Intel SGX Architectural Limitations

1. Limited EPC memory
   - Overhead up to $\times$ 1000 (SCONE [Arnautov et al., OSDI'16])

   $\rightarrow$ Cannot protect the full state using the EPC memory

2. System call restriction & enclave transitions
   $\rightarrow$ Performance loss

3. DMA directly into the enclave are not allowed
   $\rightarrow$ Large copy overhead

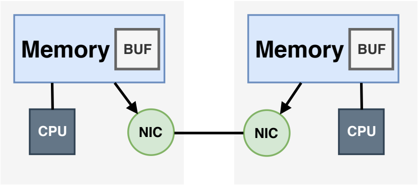


- Data copy and encryption inside the enclave **for each operation**
- Extensive server-side computation $\rightarrow$ CPU bottlenecks

Data Center Technology: RDMA

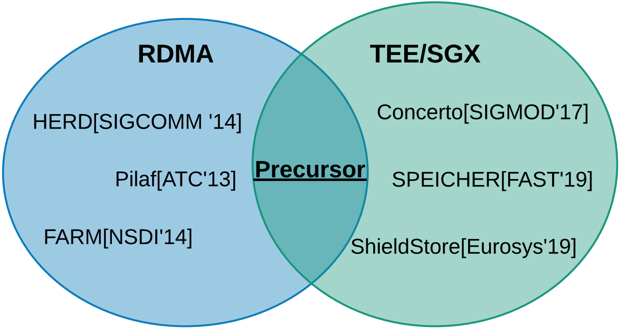
- Often employed in data centers
- Zero-copy & kernel bypassing communication
- Applications register memory with RDMA NIC

$\rightarrow$ 1-3 μs latency and **10-200 Gb/sec bandwidth** [1]



[1] https://www.mellanox.com/files/doc-2020/pb-connectx-6-en-card.pdf

Contribution

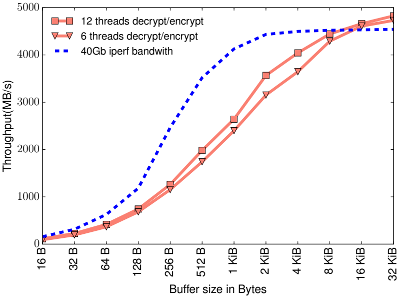


What do we gain from combining both technologies?
How to combine them efficiently?

The Cost of Cryptographic Operations

- Comparison
  - A *server-encryption* approach
  - RDMA bandwidth
- Experimental setup
  - Intel Xeon E3-2176G (6 cores, 12 hyperthreading)
  - 40 Gbit/s link
  - One-side RDMA `WRITE` using Perftest

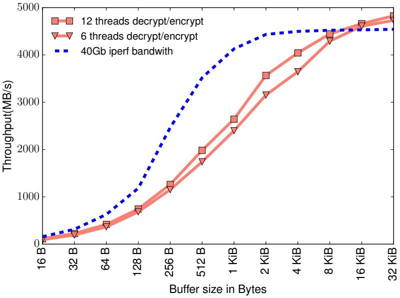
→ **36%** less throughput



The Cost of Cryptographic Operations

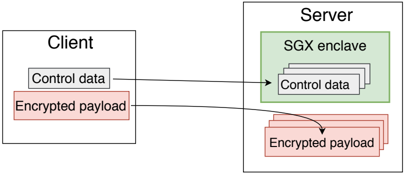
- Comparison
  - A *server-encryption* approach
  - RDMA bandwidth
- Experimental setup
  - Intel Xeon E3-2176G (6 cores, 12 hyperthreading)
  - 40 Gbit/s link
  - One-side RDMA `WRITE` using Perftest

$\rightarrow$ **36%** less throughput



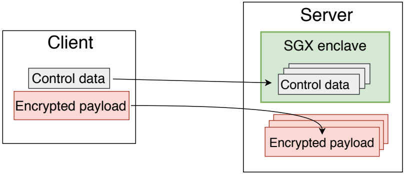
Our approach: Client-side encryption to alleviate CPU bottlenecks

PRECURSOR Approach



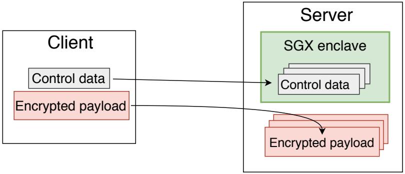
- Reduces server-side cryptographic load
  $\hookrightarrow$ Scalability: offloading cryptographic operations to the client-side

Precursor Approach



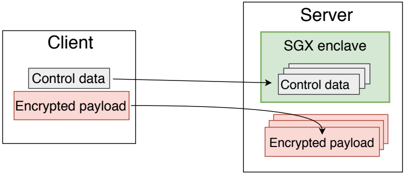
- Reduces server-side cryptographic load
  ↪ Scalability: offloading cryptographic operations to the client-side
- Mitigates SGX constraints
  ↪ Copy overhead: payload data never enters the enclave

PRECURSOR Approach



- Reduces server-side cryptographic load
  ↪ Scalability: offloading cryptographic operations to the client-side
- Mitigates SGX constraints
  ↪ Copy overhead: payload data never enters the enclave
- Integrity preserved using one time **per-operation key**
  ↪ Security: Forward secrecy and rollback attacks detection

Precursor Approach



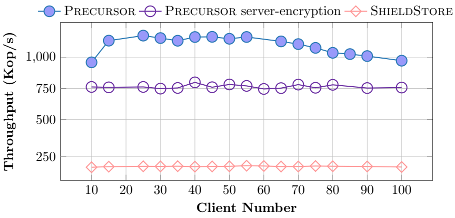
- Reduces server-side cryptographic load
  ↪ Scalability: offloading cryptographic operations to the client-side
- Mitigates SGX constraints
  ↪ Copy overhead: payload data never enters the enclave
- Integrity preserved using one time **per-operation key**
  ↪ Security: Forward secrecy and rollback attacks detection
- Use of data center network technology
  → Performance: High bandwidth and low latency

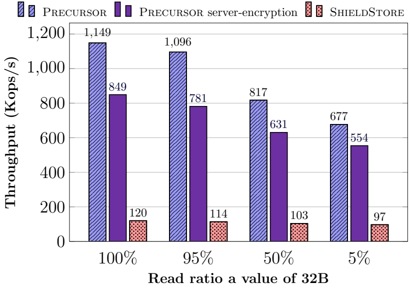
Experimental Setup

- Questions
  - How does PRECURSOR compare to existing SGX-based key value stores?
  - What is the impact of offloading on the performance?

- Workload: Yahoo! Cloud Serving Benchmark (YCSB) [Cooper et al., SoCC'10]
- Server
  - Intel Xeon E-2176G CPU (3.70 GHz, 6 cores, 12 hyper-threads)
- Client: 6 $\times$ machines
- Link: 40 Gbps RoCE NIC
- Comparison:
  - Shieldstore [Kim et al., Eurosys'19]
  - PRECURSOR variant using *server-encryption*

Evaluation





PRECURSOR scales with the number of increasing clients

PRECURSOR has 5.9-8.5 $\times$ higher throughput than SHIELDSTORE

PRECURSOR has 29%-40% higher throughput than *server-encryption* scheme

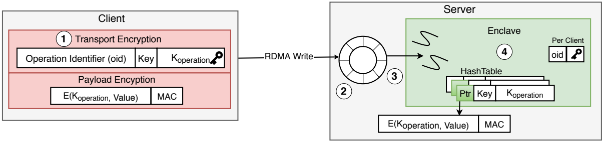
Average of 25 μs latency

PRECURSOR Take-Home Message

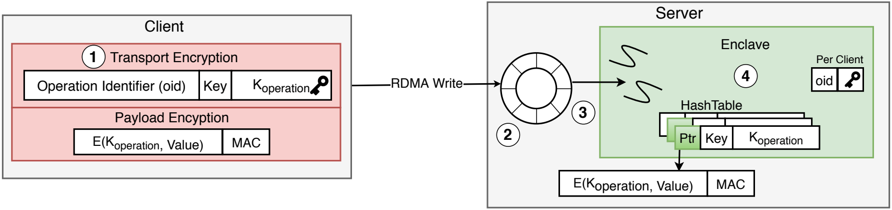
PRECURSOR: A Fast and Secure Key-Value Store

- Properties
  - Intel SGX to protect security-sensitive data
  - RDMA to achieve high-performance with low-latency
  - Client-side computation
- Lessons learned
  - Optimizing for leveraging RDMA improves the performance
  - Optimizing for CPU utilization is key for key-value stores

→ Paper: more results and technical details



Precursor Detailed Design



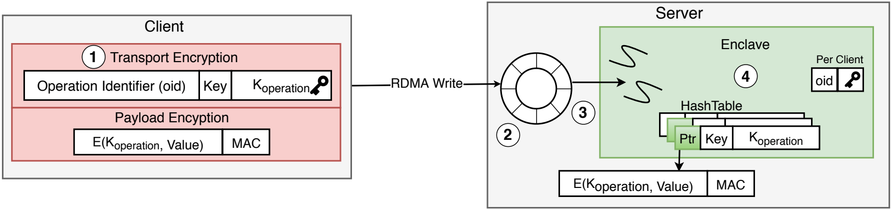
① Payload encryption and transport encryption separately

② RDMA one-sided write in pre-allocated buffer in the server memory

③ Security metadata in the enclave while payload remains untrusted

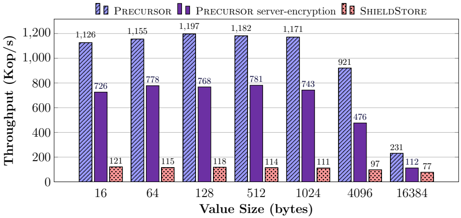
④ The enclave stores the hash table with the security metadata and the pointers to the respective payload data

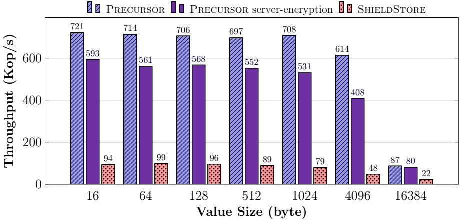
PRECURSOR Guarantees



- One-time keys for the payload is robust and preserves forward secrecy
- MAC verification ensures integrity and rollback attacks detection
- No re-encyptions once a client is excluded from accessing the service

Evaluation: Throughput

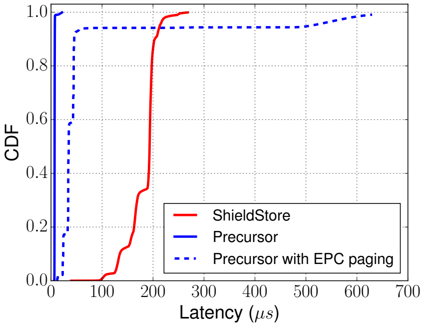




Question: what is the impact of varying value sizes?

→ *server encryption* decreases the throughput with an average of **49%** for a read-only and **27%** for a update-mostly workload

Evaluation: Tail Latency



Question: how does the tail latency perform?

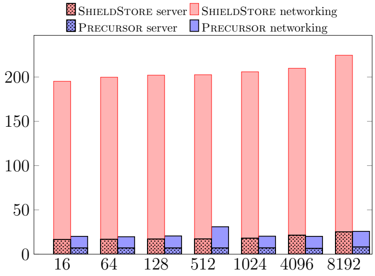
→ PRECURSOR has lower GET() tail latencies

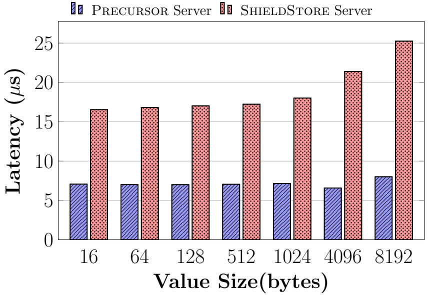
→ Latency steady until 95% at a 8 μs

→ EPC impact is apparent from 95%

Evaluation: Latency Analysis

Question: what is the network impact vs. security protection technique?





→ Precursor has faster server processing that keeps steady with increasing payload size

Conclusion

Challenge: How to leverage SGX for securing key-value stores and how to secure applications that utilize RDMA?

- PRECURSOR: a key-value store with strong confidentiality & integrity
  - Lowers the server-load to benefit from RDMA
  - Reduces the copy overhead and keeps a small TCB
  - Achieves high throughput than existing SGX-based key-value stores

Questions?

messadi@ibr.cs.tu-bs.de