

ECE 209AS (03/19/2020) Final Presentation

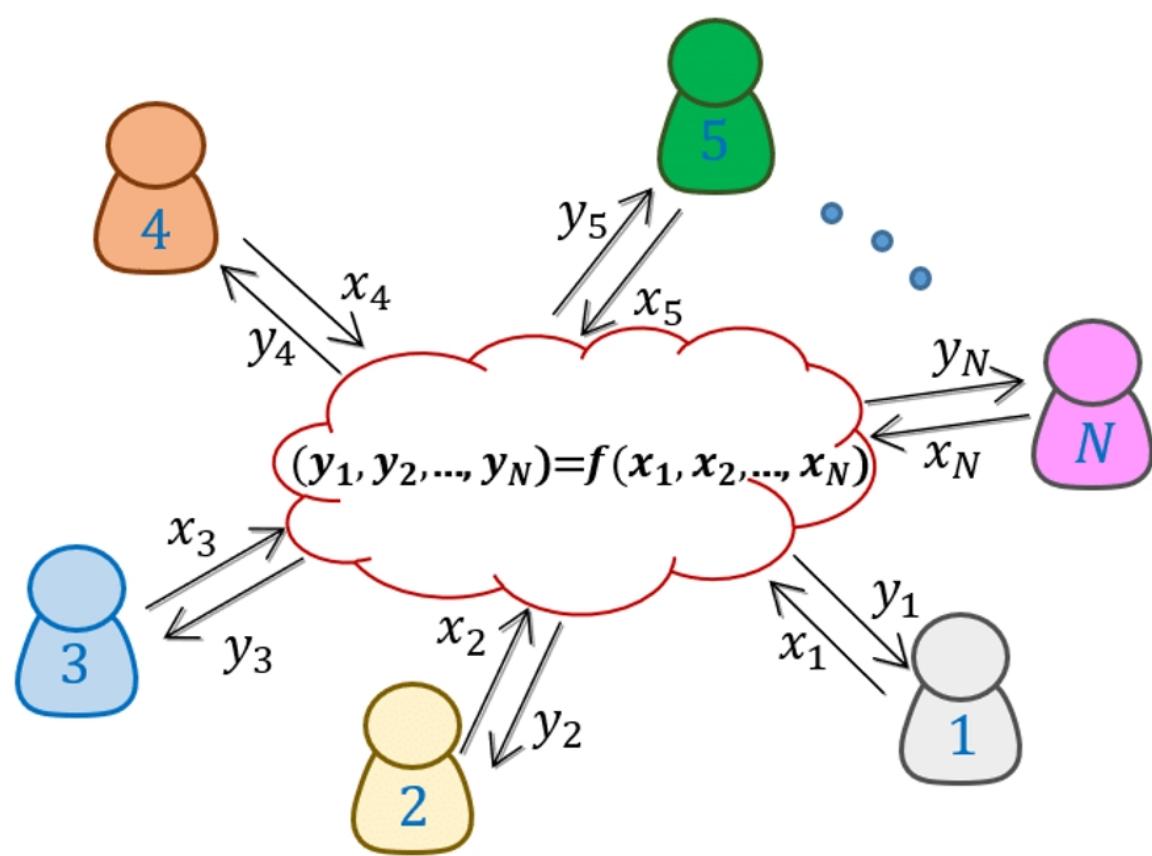
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# P2I: Privacy Preserving Inferencing for Medical Cyberphysical Systems

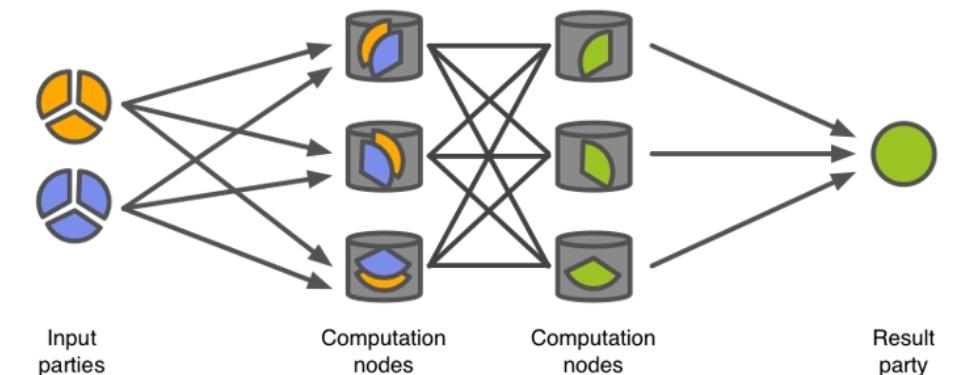
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Team Members: Swapnil Sayan Saha, Vivek Jain and Brian Wang

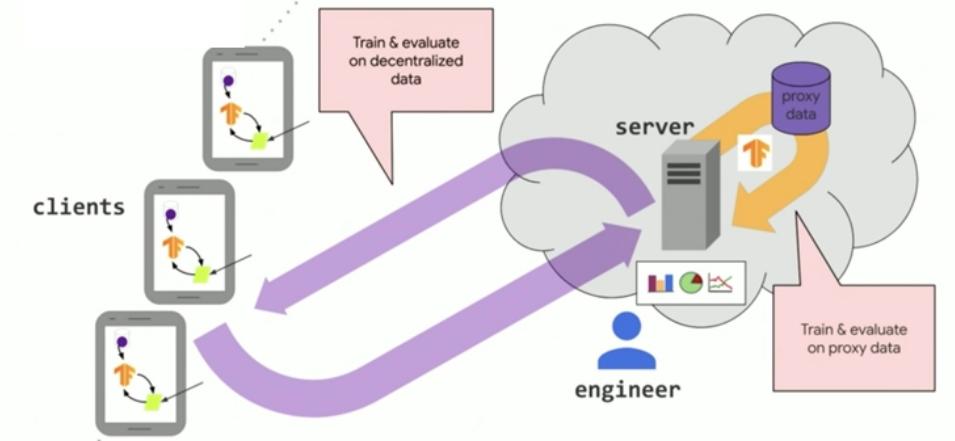
# Problem Statement and Importance



Perform collaborative computation without revealing raw data

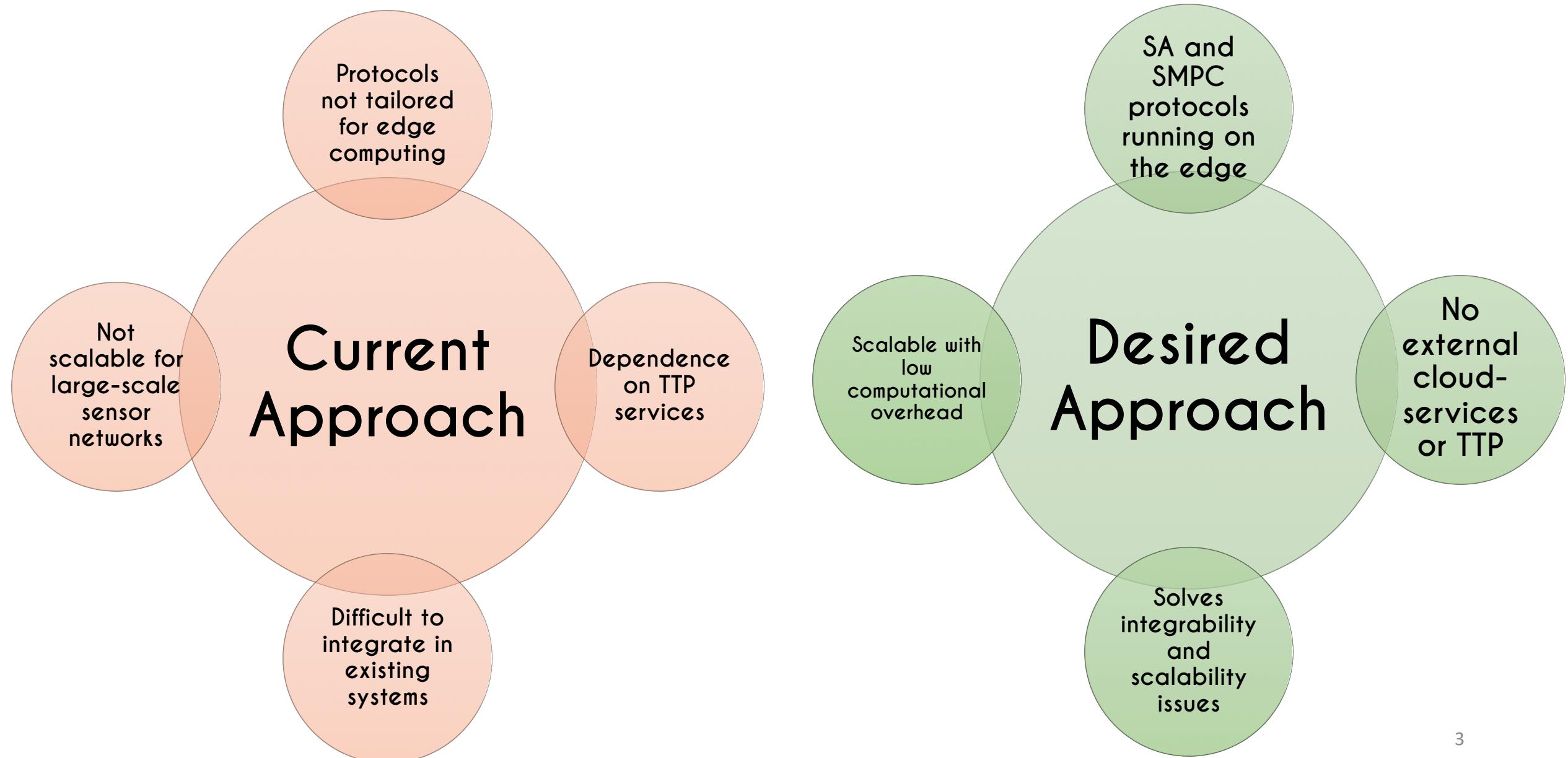


Secure Multi-Party Computation



Secure Aggregation

# Problem Statement and Importance (contd.)



# Overall Project Goals and Specific Aims

## Specific Aims

Implement state-of-the-art SMPC and SA protocols in small-scale virtual MCPS, with computation occurring at the edge.

Benchmark standard performance, privacy and security metrics of implemented SMPC and SA.

Tune the parameters of state-of-the-art SMPC and SA protocols, focusing on reducing computational overhead.

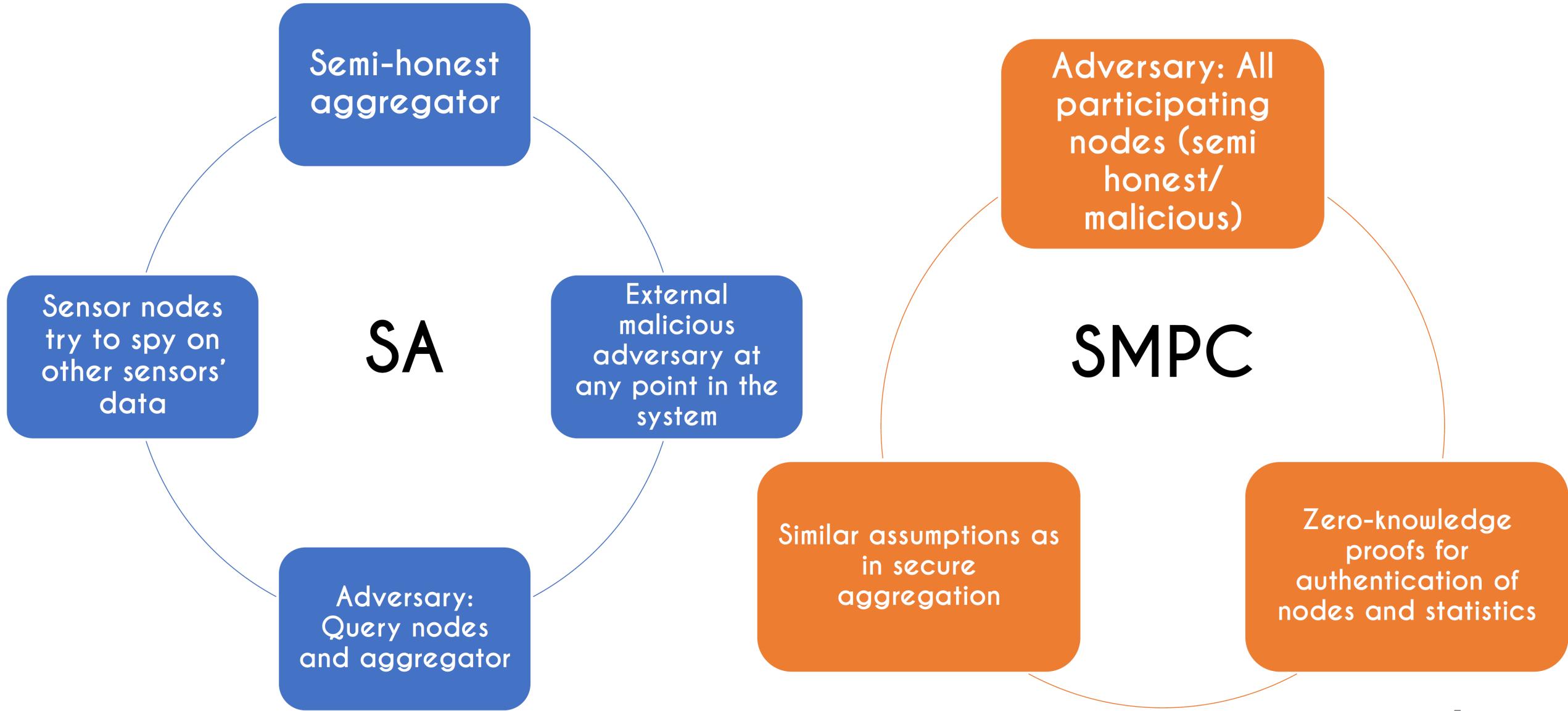
Implement a scalable and robust star-exchange MCPS topology embracing SMPC protocols void of centralized cloud inferencing.

## Deliverables / Goals

Benchmark and tune SMPC and SA protocols for resource-constrained settings

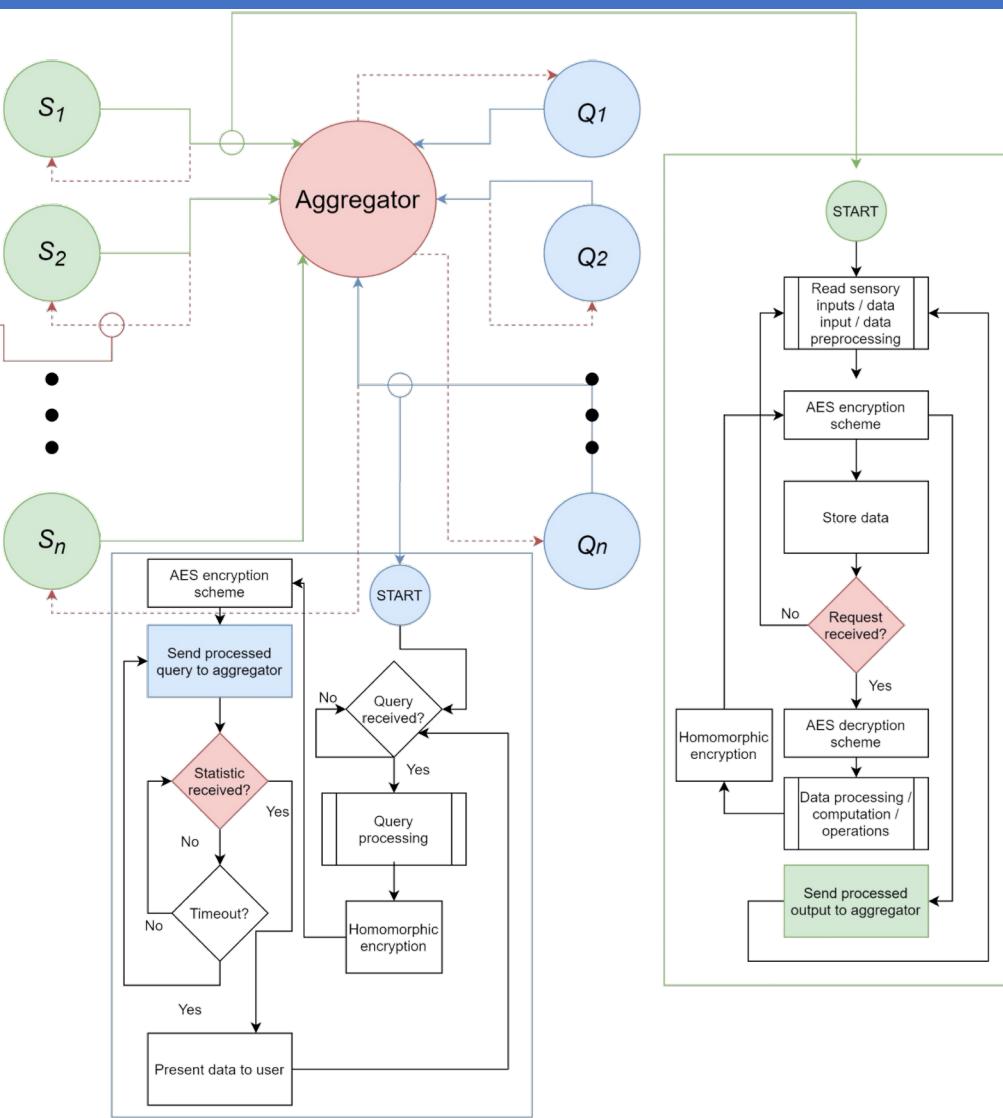
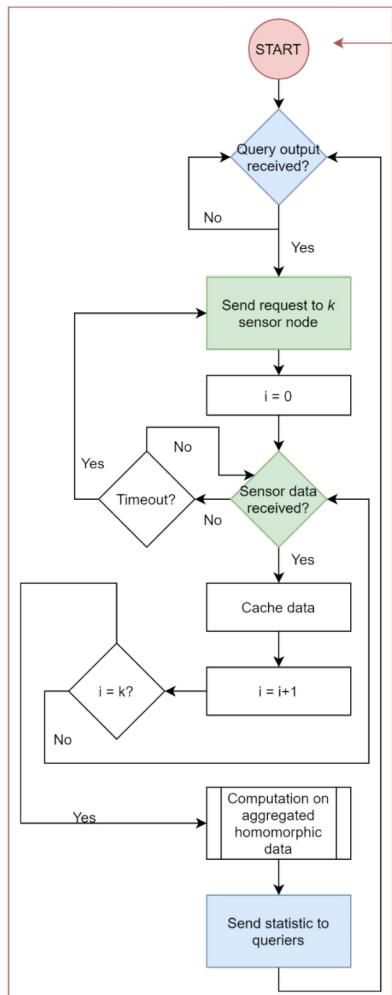
A real-time scalable and robust privacy preserving inferencing system at the edge for MCPS

# Attack Model



# Technical Approach (Secure Agg.)

Paillier cryptosystem  
with star topology



## Key Generation:

- ▶  $pk = (n, g)$ 
  - $n = pq, GCD(pq, (p-1)(q-1)) = 1$
  - $g \in \mathbb{Z}_{n^2}^*$
- ▶  $sk = (\lambda, \mu)$ 
  - $\lambda = LCM(p-1, q-1)$
  - $\mu = (\frac{g^\lambda \bmod n^2 - 1}{n})^{-1} \bmod n$

## Encrypt message into ciphertext:

- ▶  $c = g^m \cdot r^n \bmod n^2, r \in \mathbb{Z}_n$

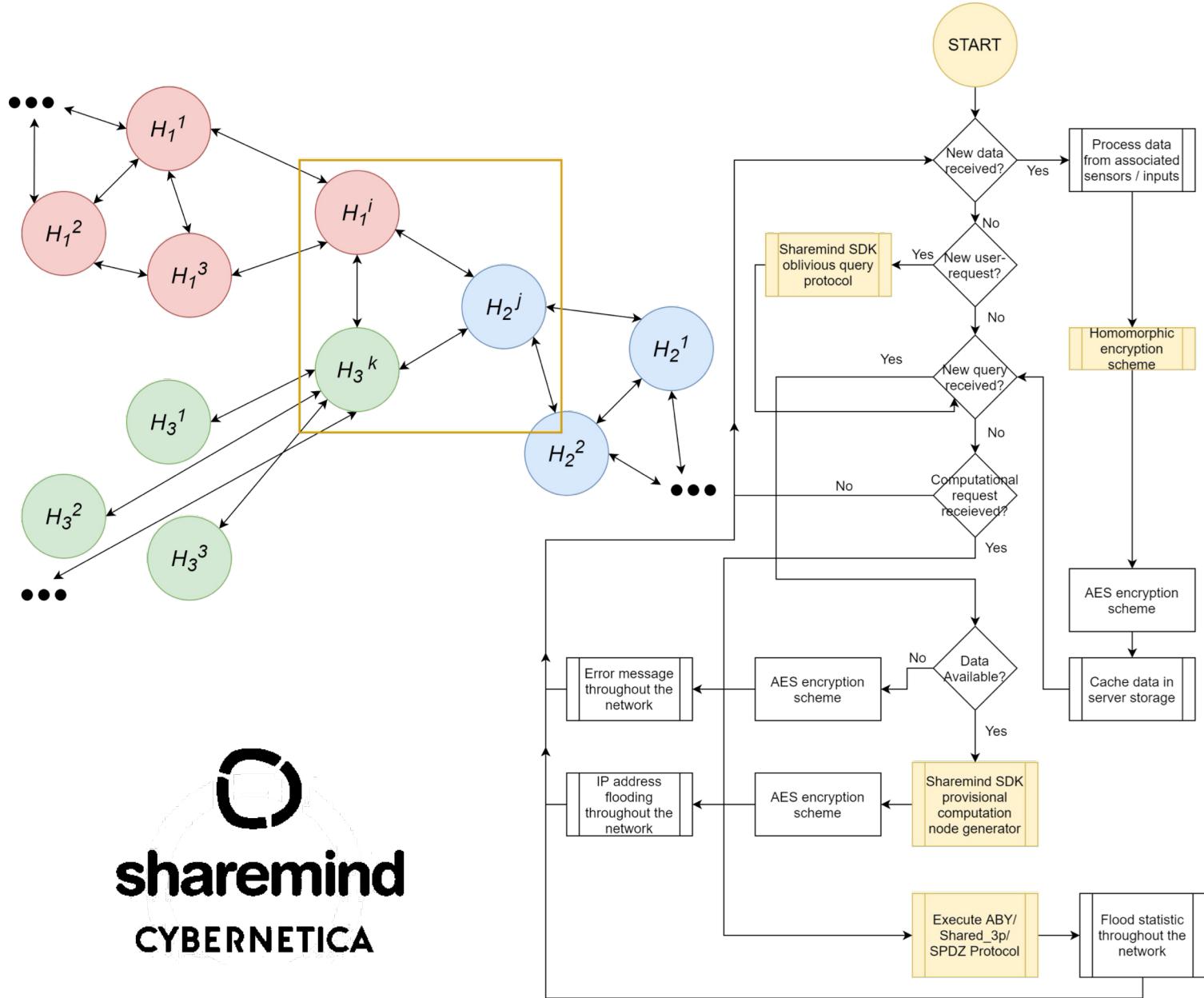
## Decrypt ciphertext into message:

- ▶  $m = \frac{c^\lambda \bmod n^2 - 1}{n} \cdot \mu \bmod n$

## Homomorphic property:

$$\begin{aligned}
 D(E(m_1, r_1) \cdot E(m_2, r_2) \bmod n^2) &= m_1 + m_2 \bmod n. \\
 D(E(m_1, r_1) \cdot g^{m_2} \bmod n^2) &= m_1 + m_2 \bmod n. \\
 D(E(m_1, r_1)^k \bmod n^2) &= km_1 \bmod n.
 \end{aligned}$$

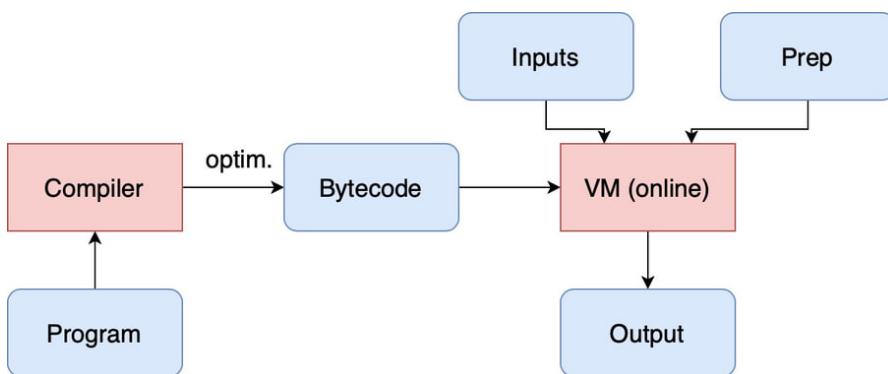
# Technical Approach (SMPC)



# Technical Approach (SMPC)

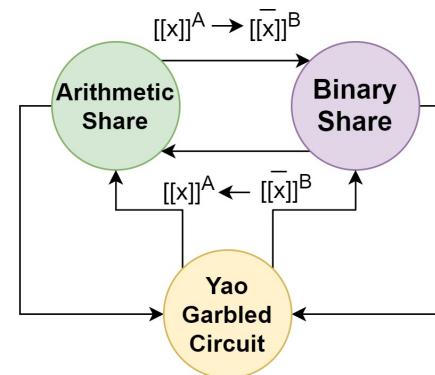
## SPDZ:

- An input  $a \in \mathbb{F}_{p^k}$  is represented as  $\langle a \rangle = (\delta, (a_1, \dots, a_n), (\gamma(a)_1, \dots, \gamma(a)_n))$ ,  $a_i$  is a share of  $a$  and  $\gamma(a)_i$  is the MAC share authenticating  $a$  under a SPDZ global key  $\alpha$  (not revealed until end). Player  $i$  holds  $a_i, \gamma(a)_i$  and  $\delta$  is public.
- Correct SPDZ execution:  $a = \sum_i a_i, \alpha(a + \delta) = \sum_i \gamma(a)_i$
- Two phases - offline: generates precomputed values (independent of the function); online: executes designated function using the values.



## ABY

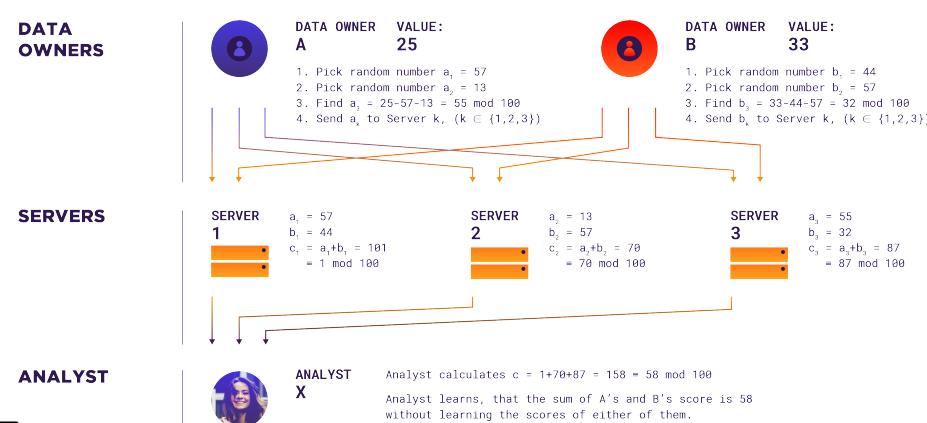
- Arithmetic, binary and Yao 3PC
- 3PC with secret sharing for privacy preserving machine learning and database joins (PSI, Union, etc.); secure against semi-honest adversaries;
- Randomly goes back and forth between A, B and Y.



$$\begin{aligned} [[x]]^A &= \sum_i x_i \\ [[x]]^B &= x_1 \oplus x_2 \oplus x_3 \\ [[x]]^Y &= LSB(x_1 \oplus x_2) \\ x &= x_1 + x_2 + x_3 \end{aligned}$$

## Shared3p

- Sharemind's proprietary MPC.
- 3PC with secret sharing; secure against semi-honest adversaries
- Uses the additive secret sharing scheme in the ring  $\mathbb{Z}_2(32)$ .



# Technical Approach (oblivious functions)

## Implemented SA operations (Language: Python)

Mean	Convolution	Linear Regression
Vector Sum		

## Implemented SMPC operations (Language: SecreC)

Shuffle	Quicksort	Outer join
Union	Intersection	MAD
Mean	Median	Upper Quantile
Lower Quantile	Minimum	Maximum
StdDev	Variance	Vector Sum (VS)
Outlier_MAD	Outlier_Quantile	Linear Regression
Obv_Insert		

\* mean implemented for all 3 protocols

The image shows a technical environment for developing and running secure multi-party computation (SMPC) applications. It includes:

- Terminal Window:** Displays Python code for generating Paillier keypairs and performing oblivious operations like vector summation.
- Qt Creator IDE:** Shows SecreC source code for implementing oblivious functions like union, intersection, and various statistical operations (Mean, Median, Quantiles, StdDev, Variance).
- Sharemind Application Server Log:** Shows the execution of a test script named 'test1.sc' on the 'sharemind-sdk-release\_2019.03' server. The log output includes the estimated running time (46312685 microseconds) and a note about the estimated running time on a Gbit network.

```

import numpy as np
import time
public_key, private_key = paillier.generate_paillier_keypair(n_length=1024)

elapsed_total_add = 0
elapsed_total_mult = 0
for i in range(100):
    a = np.random.randint(0, high=256)
    b = np.random.randint(0, high=256)
    encrypted_a = public_key.encrypt(a)
    encrypted_b = public_key.encrypt(b)
    start_time = time.process_time()
    for j in range(10000):
        adder = a+b
    elapsed = (time.process_time() - start_time)
    elapsed_total_add += elapsed
    start_time = time.process_time()
    for j in range(10000):
        mult = a * b
    elapsed = (time.process_time() - start_time)
    elapsed_total_mult += elapsed
X=[]
for c in range(data[step:c: step*(c+1)]):
    X.append(X)
X = np.asarray(X)
key_length = 1024

class Client:
    def __init__(self, X, pubkey=None, privatekey=None):
        self.pubkey = pubkey
        self.privatekey = privatekey
        self.X = X

    def mean(self):
        return np.mean(self.X)

    def encrypt_mean(self):
        return self.pubkey.encrypt(self.mean())

    def decrypt_mean(self, mean_server):
        return self.privatekey.decrypt(mean_server)

    _square_sum(self):
        self.pubkey.encrypt(np.sum(np.square(self.X)))

    _mean(self, mean_server):
        self.privatekey.decrypt(mean_server)
    
```

```

//secure union and intersection using oblivious functions
pd_shared3p float64[[1]] intersectAB(size(joinAB));
uint k = 0;
for(uint i = 0; i < size(sharedA); ++i){
    for(uint j = 0; j < size(partyB); ++j){
        pd_shared3p bool[0] truecond = true;
        pd_shared3p bool[0] falsecond = false;
        pd_shared3p bool[0] cond = choose(sharedA[i], partyB[j]);
        if(declassify(cond)){
            intersectAB[k] = sharedA[i];
            k++;
        }
    }
}
intersectAB = intersectAB[0:k];
pd_shared3p float64[[1]] unionAB(size(joinAB));
uint f = 0;
k = 0;
for(uint i = 0; i < size(sharedA); ++i){
    unionAB[k] = sharedA[i];
    k++;
}
for(uint i = 0; i < size(partyB); ++i){
    for(uint j=0; j<size(sharedA); ++j){
        pd_shared3p bool[0] truecond = true;
        pd_shared3p bool[0] falsecond = false;
        pd_shared3p bool[0] cond = choose(sharedA[i], partyB[j]);
        if(declassify(cond)) {
            f = 1;
        }
    }
}
    
```

```

/* Secure MPC Emulation Demo. (c) 2020 Swapnil Sayan Saha */
import shared3p;
import stdlib;
import shared3p_random;
import shared3p_sort;
import shared3p_statistics_summary;
import shared3p_statistics_outliers;
import shared3p_statistics_distribution;
import shared3p_statistics_regression;
import oblivious;
import shared3p_oblivious;
import aby;
import spdz_fresco;
domain pd_shared3p shared3p;
domain pd_spdz_fresco spdz_fresco;
domain pd_aby aby;

//secure user defined function to calculate vector sum
templatedomain D : shared3p, type T>
D T[[1]] vecSum(D T[[1]] x, D T[[1]] y, D T[[1]] z){
    return sqrt((x*x)+(y*y)+(z*z));
}

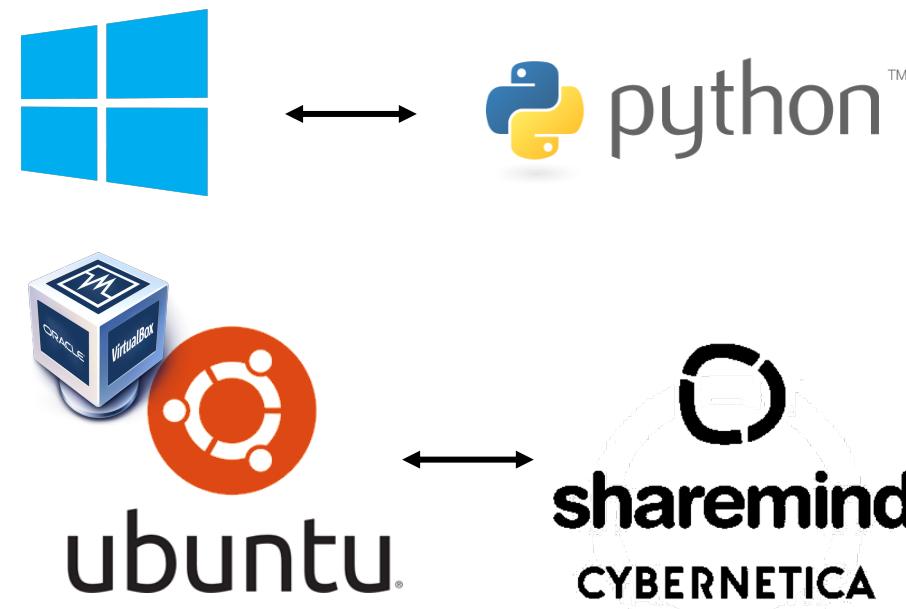
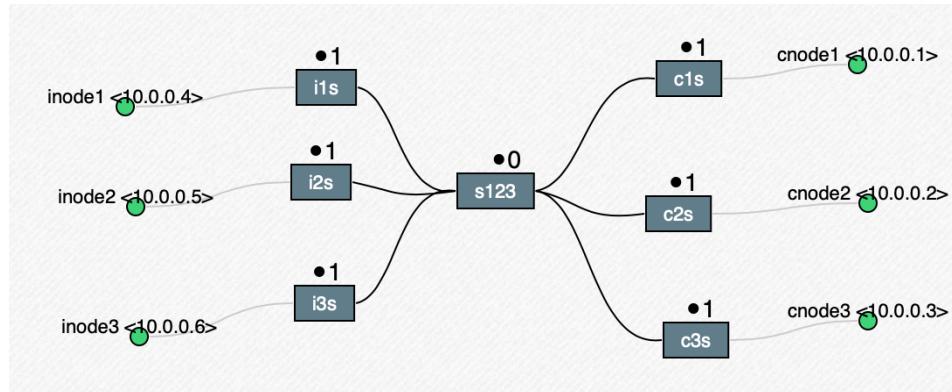
General Messages > < 
{72.78700000000001, 62.611, -7.92}
{777.62, 611, -7.92}
10
10
10
Process returned status: 0
Estimated running time: 46312685 microseconds (46 seconds)
(This is the estimated running time of the program on the Sharemind Application Server, running on a Gbit network)
    
```

# Experimental Setup

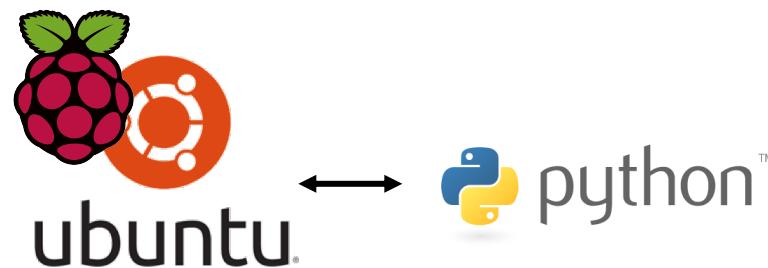
## Preliminary Benchmarking and Prototyping:

SDN Narmox Spear – Mininet

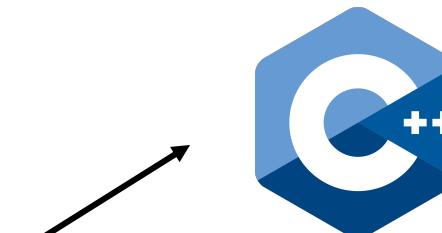
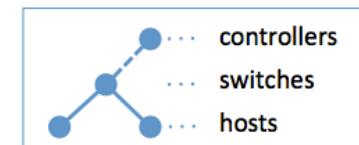
<http://demo.spear.narmox.com/app/?apiurl=demo#/mininet>



## Real-time Benchmarking/Implementation

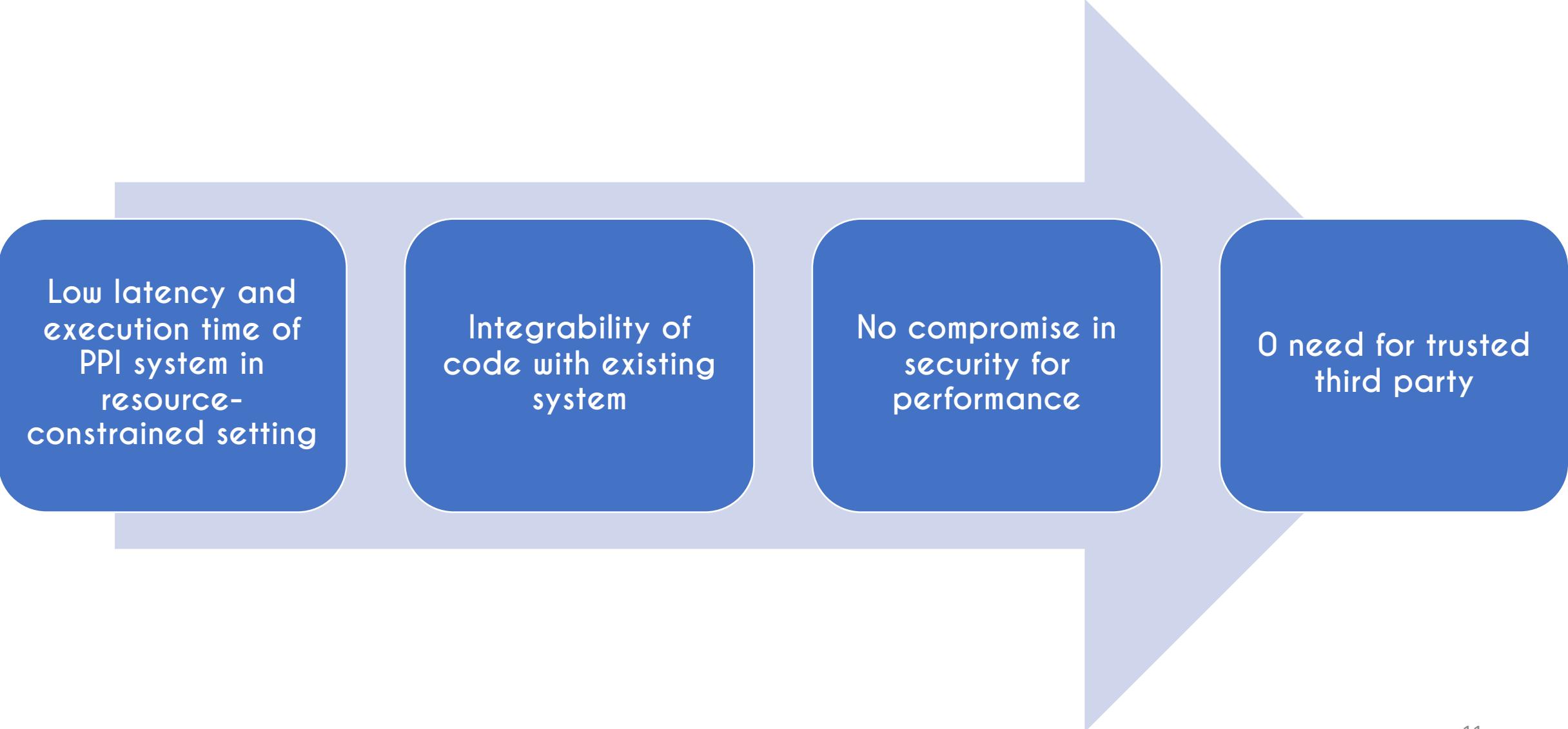


> sudo mn



↔ python

# Success Metrics



Low latency and execution time of PPI system in resource-constrained setting

Integrability of code with existing system

No compromise in security for performance

0 need for trusted third party

# Implementation / Demo

Real-time secure aggregation demo on Mininet:

<https://www.youtube.com/watch?v=DHPKwDjj1qg>

Real-time SMPC demo on Mininet:

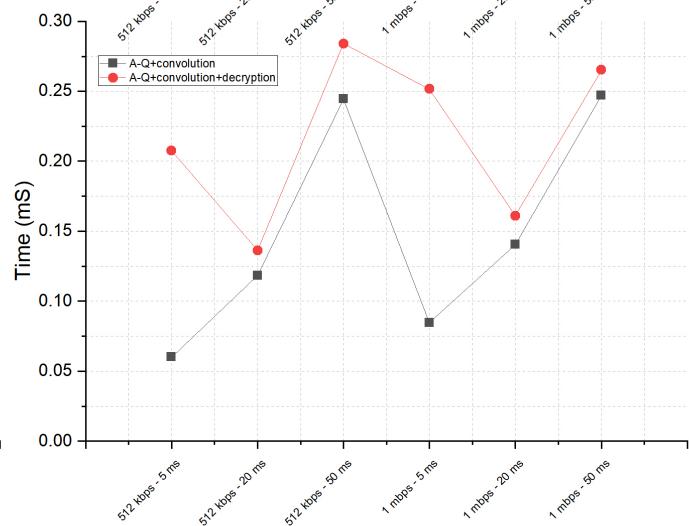
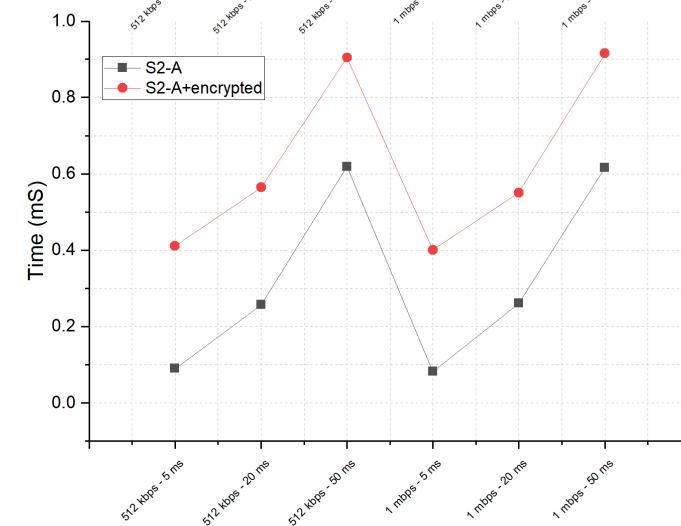
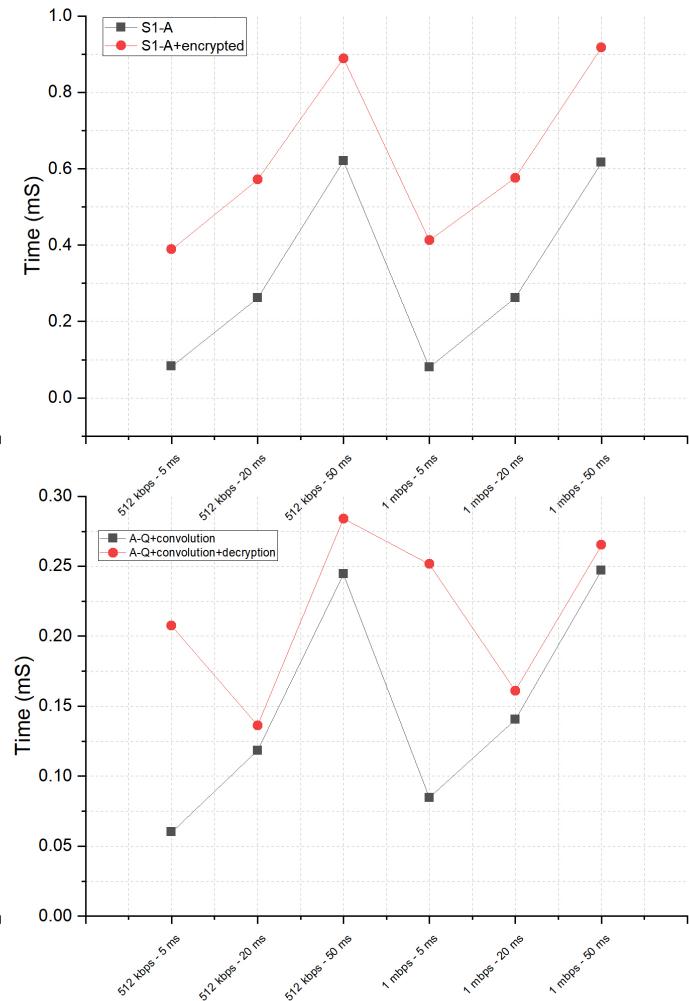
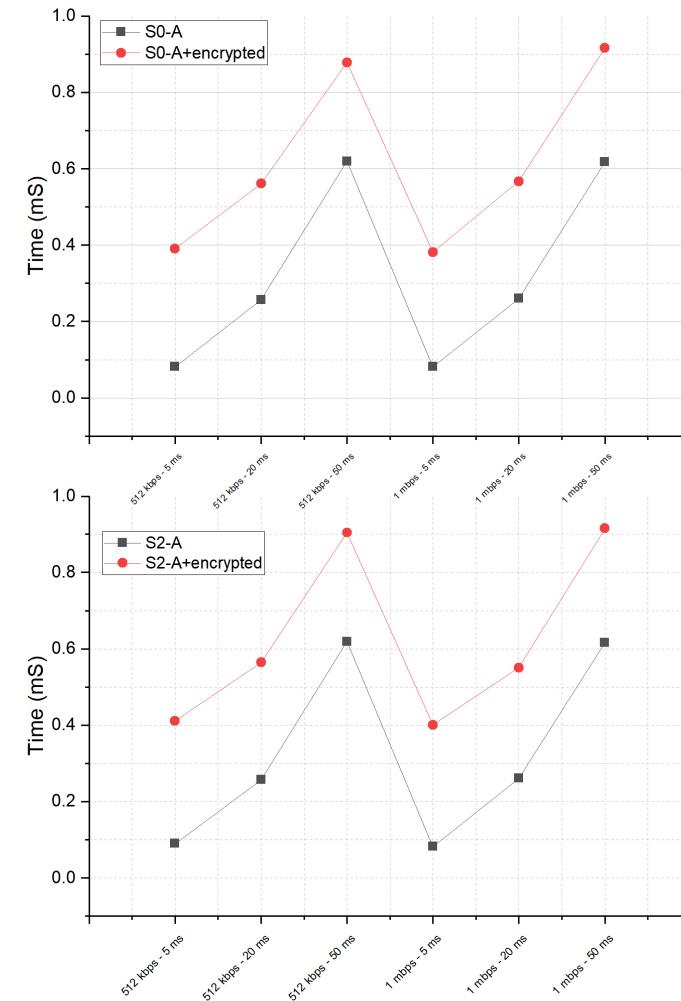
[https://www.youtube.com/watch?v=t\\_OHudujrkc](https://www.youtube.com/watch?v=t_OHudujrkc)

# Key Findings (SA)

SA standalone benchmark metrics:

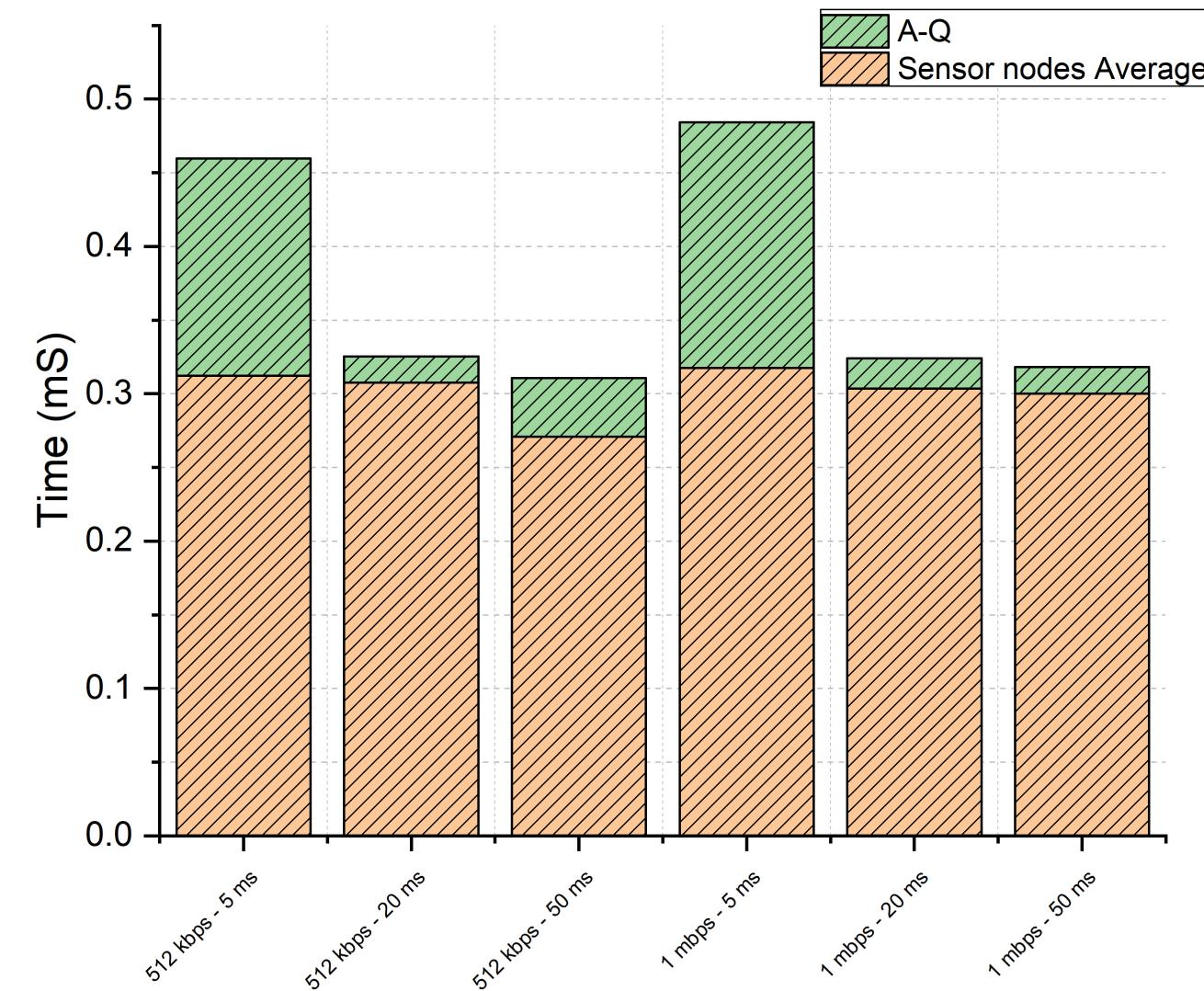
Parameter	I7-6700 HQ, 16 GB RAM (Macbook)	Raspberry Pi 4
Memory Usage	~ 15 Mb	~ 36 Mb
CPU Usage	99.7%	99.7%
Key Generation (mS)	141.65	122.96
Encrypted Scalar Addition (uS)	15.01	49.77
Encrypted Scalar Multiplication (uS)	103.67	339.36
Normal Scalar Addition (nS)	115.73	493.51
Normal Scalar Multiplication (nS)	101.63	376.07

SA real-time communication delays (encrypted vs normal) for various network speeds and latencies:



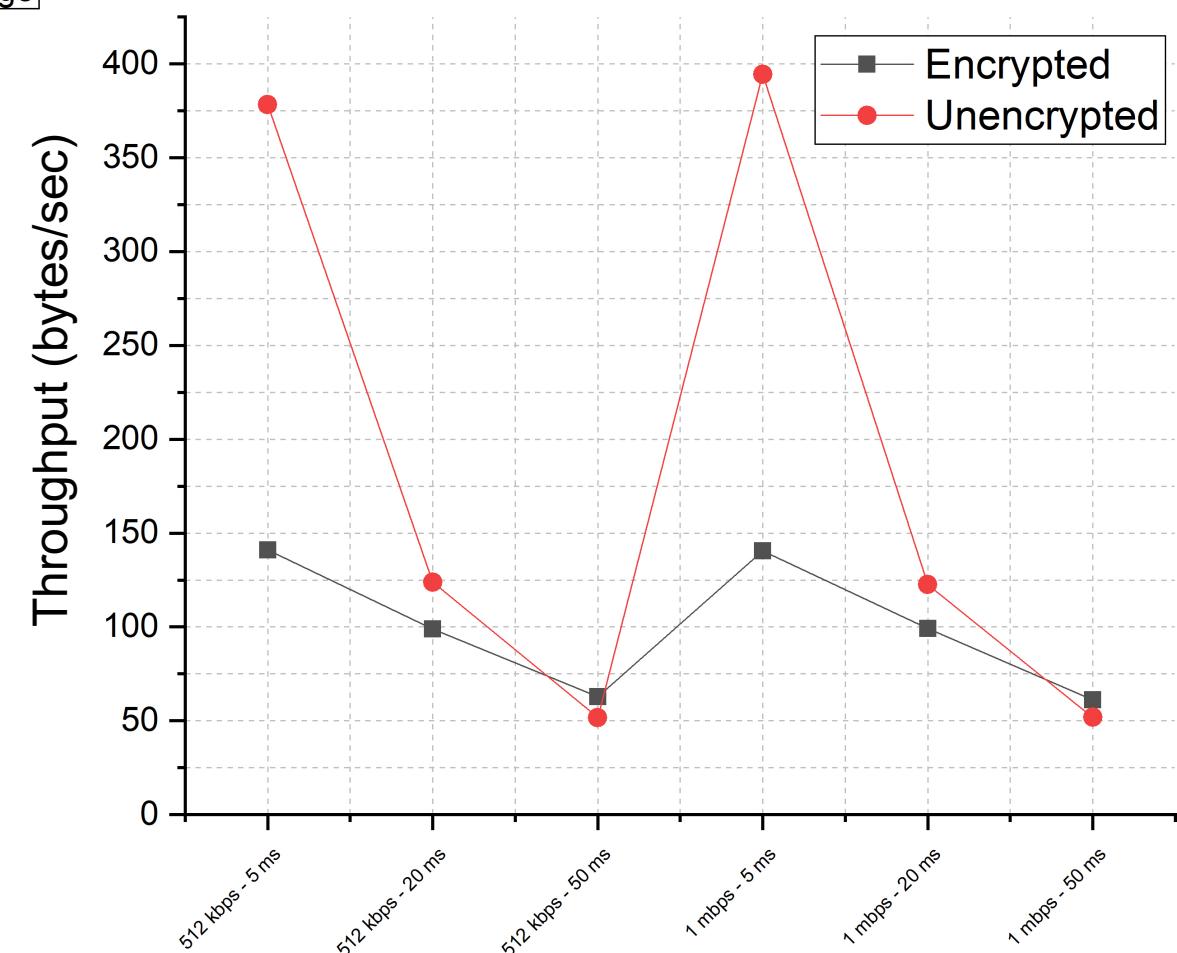
# Key Findings (SA)

SA real-time overhead (encrypted) for various network speeds and latencies:



SA real-time throughput (encrypted vs normal) for various network speeds and latencies:

- Worst case sampling rate: 60 Hz.



# Key Findings (SMPC)

SMPc Standalone benchmark metrics:

Preliminary benchmark results\* (-microseconds (CPU usage)):

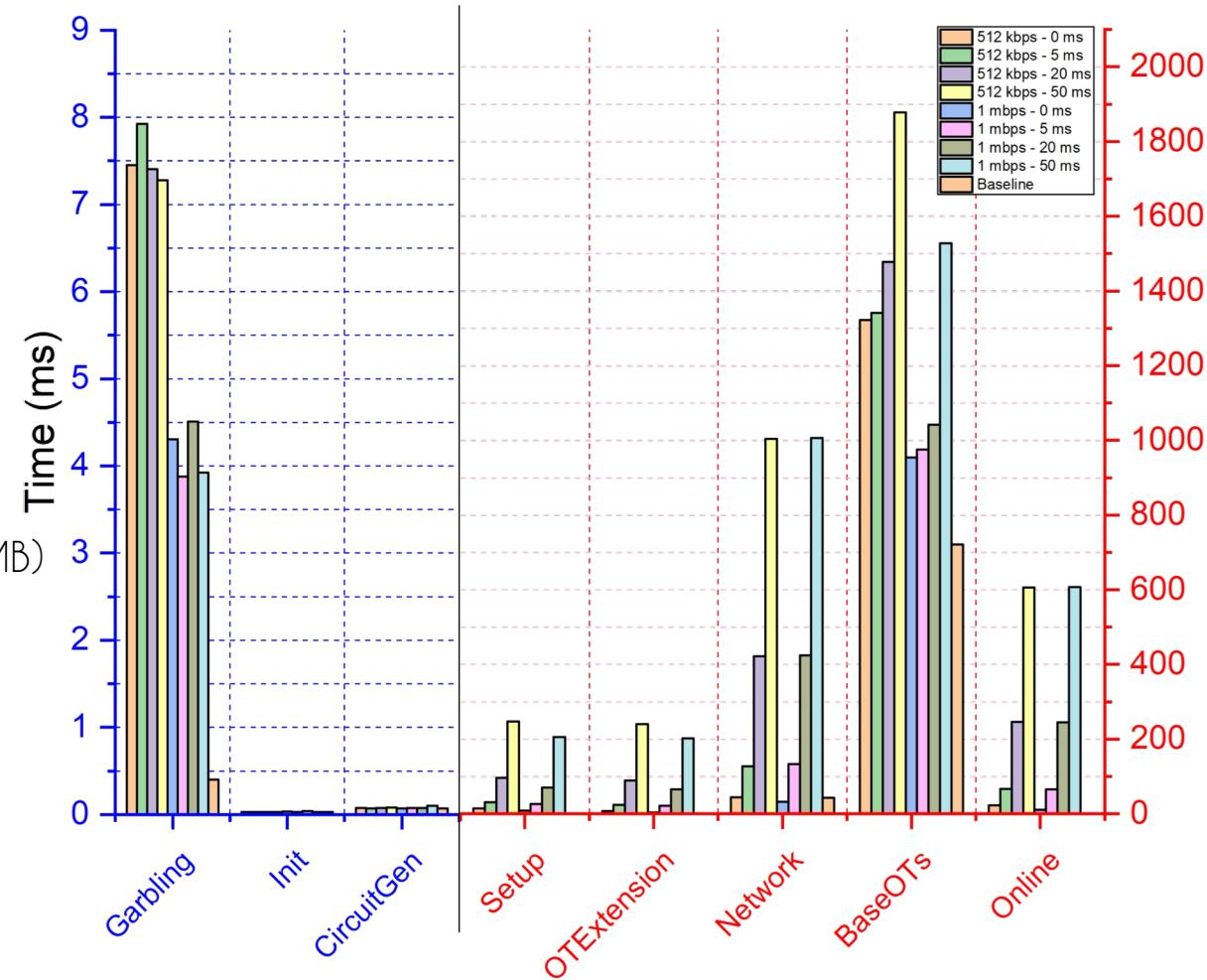
	ABY	Shared 3p	SPDZ Fresco
Scalar Addition (+ encryption)	11373 (9%)	104 (11%)	18149 (10%)
Scalar Multiplication (+ encryption)	8055 (11%)	397 (14%)	25685 (10%)

\* on single core AMD64 architecture, 1 GB RAM (RAM usage: 173 MB)

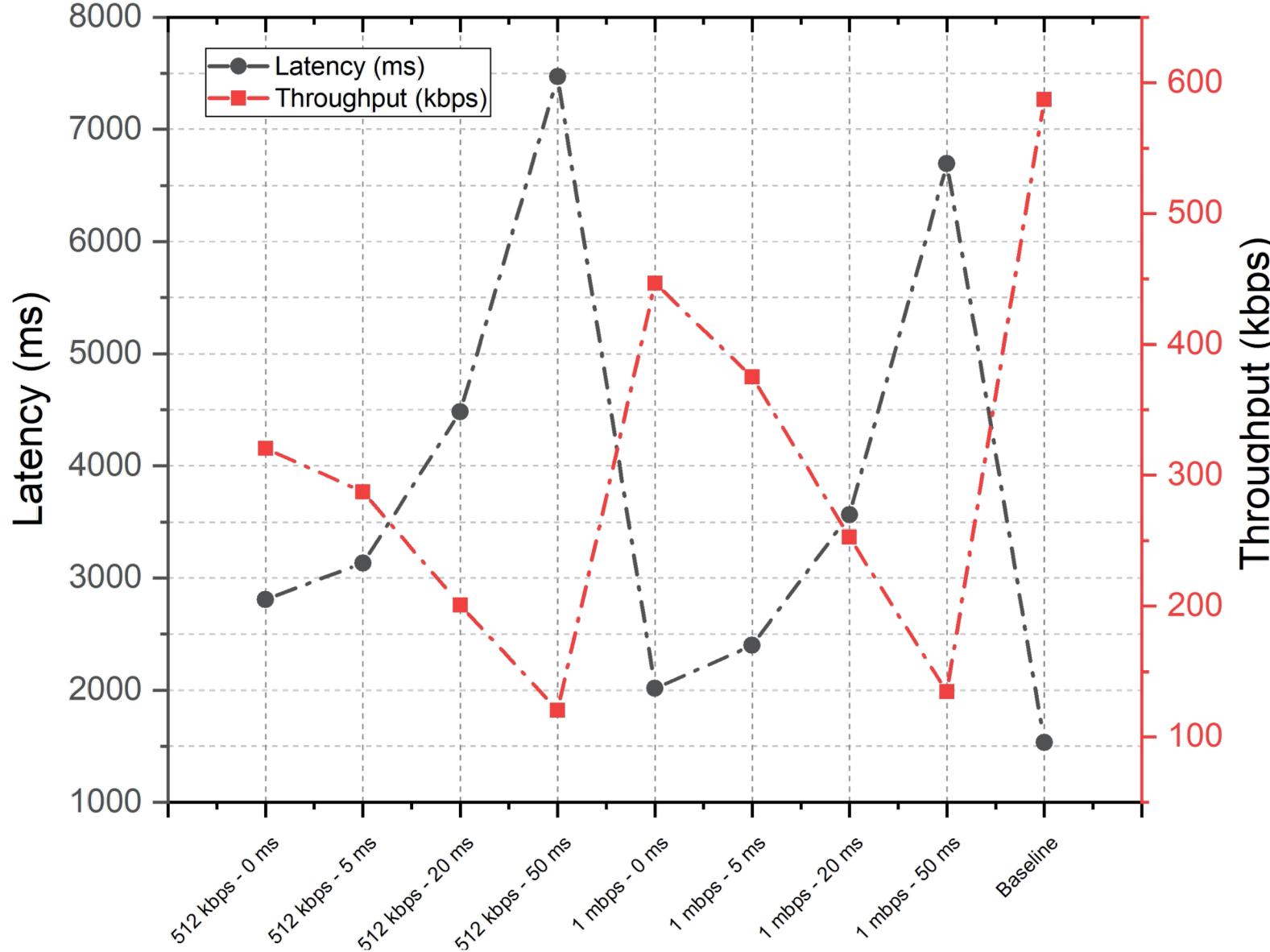
Normal scalar addition: 11.04 us

Normal scalar multiplication: 32.45 us

ABY SMPc real-time delays at each step for various network speeds and network latencies (Millionaire's Problem):



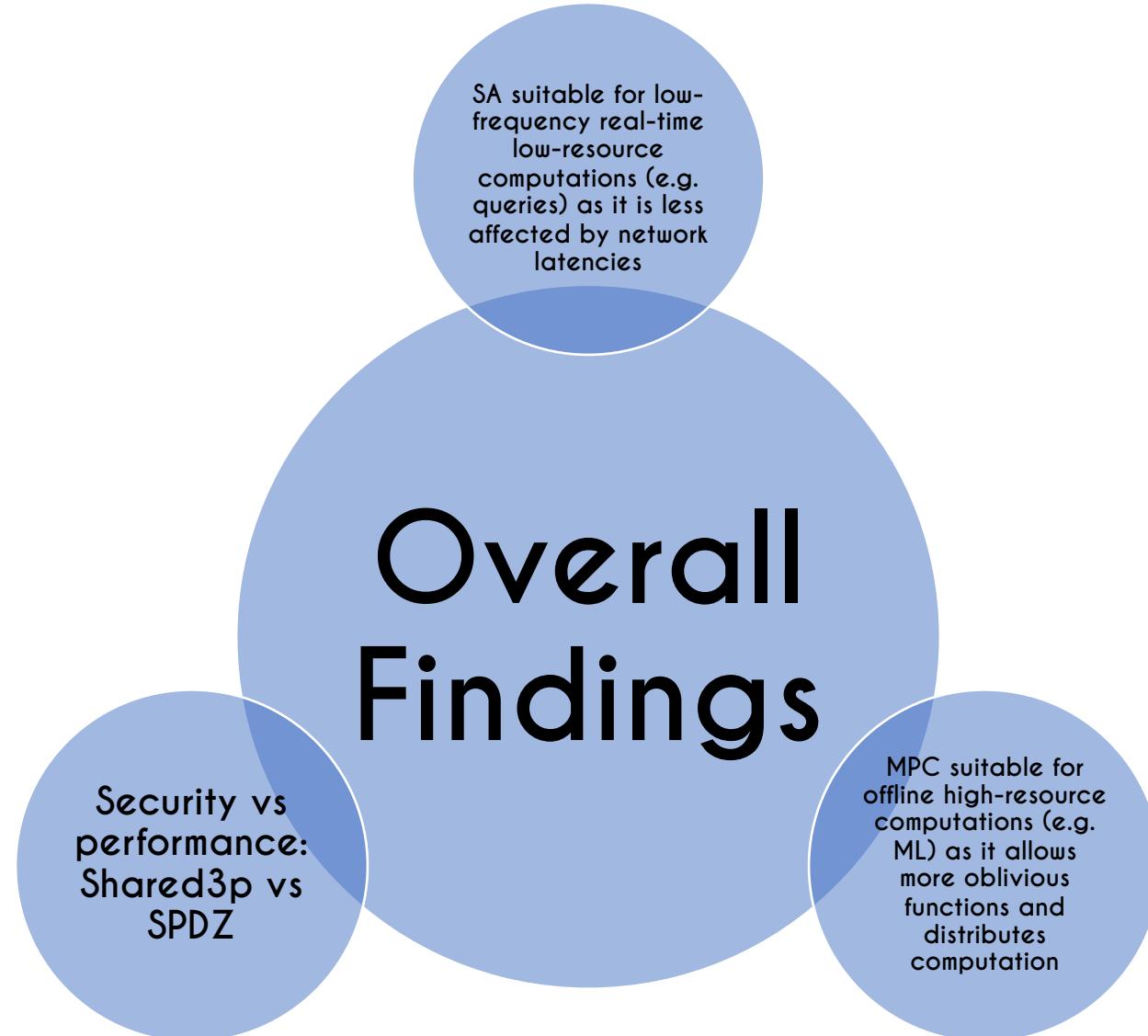
# Key Findings (SMPC)



ABY SMPC real-time output latencies and throughputs for various network speeds/latencies (baseline assumes 0 network latency at 100 Mbps)

- Worst case sampling rate: 15 Hz.

# Key Findings (Overall)



# Prior Work and Relative Novelty

Work	Functionality	n-party?	Malicious security?	Practical?
Nikolaenko et al. [60]	ridge regression	no	no	-
Hall et al. [45]	linear regression	yes	no	-
Gascon et al. [38]	linear regression	no	no	-
Cock et al. [21]	linear regression	no	no	-
Giacomelli et al. [39]	ridge regression	no	no	-
Alexandru et al. [5]	quadratic opt.	no	no	-
SecureML [58]	linear, logistic, deep learning	no	no	-
Shokri&Shmatikov [70]	deep learning	not MPC (heuristic)	no	-
Semi-honest MPC [7]	any function	yes	no	-
Malicious MPC [28, 41, 11, 2]	any function	yes	yes	no
<b>Our proposal, Helen:</b> regularized linear models		yes	yes	yes

Our work

- Zheng et al. [1] hypothesized that it is not possible to achieve robust and practical MPC using existing state-of-the-art protocols on the edge.
- Helen requires powerful server-class machines to operate.

Our benchmark shows that it is possible to solve classical MPC (and SA) problems and queries on resource-constrained edge devices using existing state-of-the-art MPC (and SA) protocols.

[1]. Zheng, Wenting, et al. "Helen: Maliciously secure competitive learning for linear models." *2019 IEEE Symposium on Security and Privacy (SP)*. IEEE, 2019.

# Prior Work and Relative Novelty

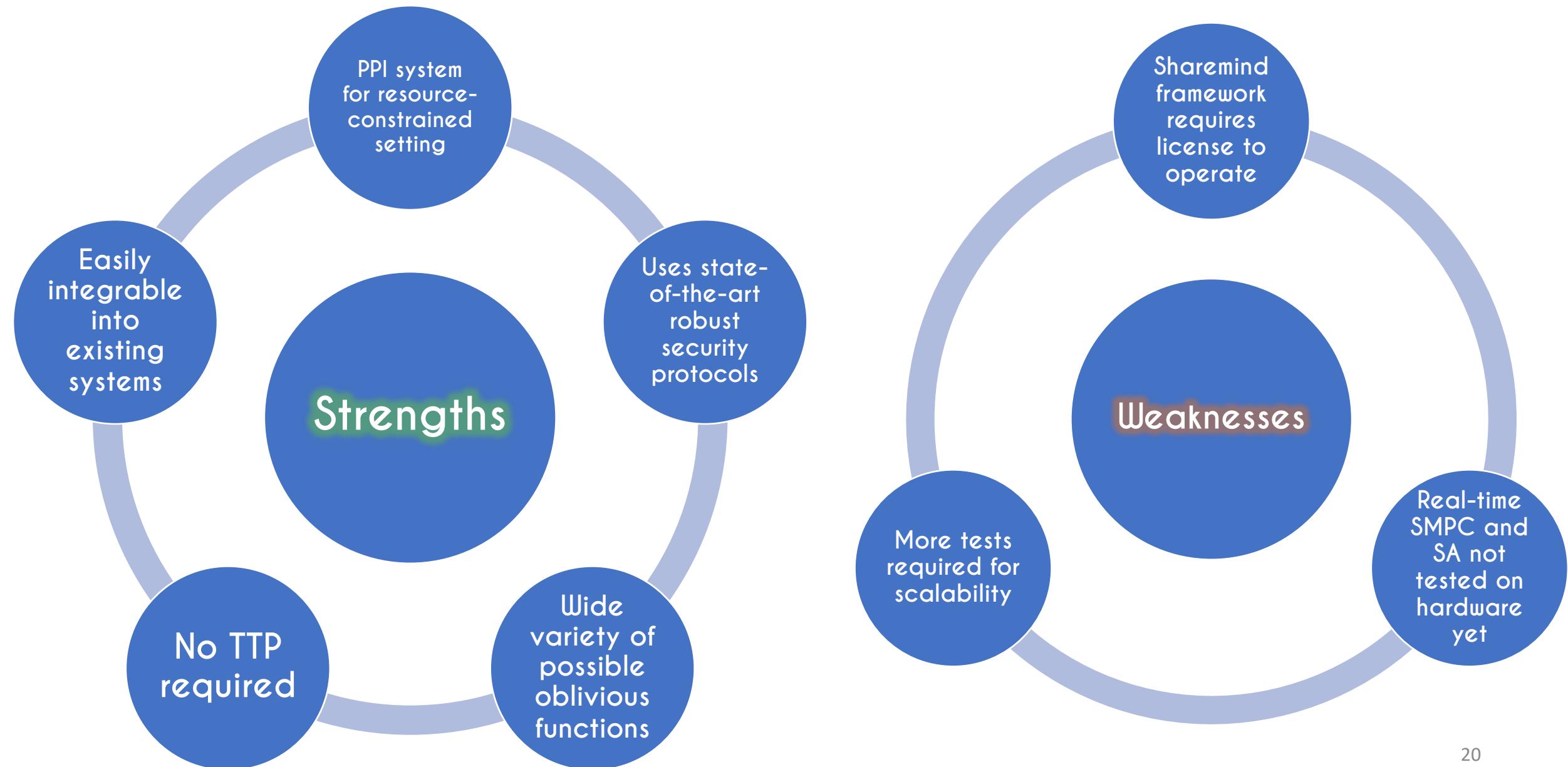
- Several MPC and SA architectures have been proposed in literature for MCPS (populated in website)
- All of the proposals, while secure from an information-theoretic view, require some notion of cloud services or external trusted third party, breaking Lindell's [1] recommendations.

*"...the key challenge in secure MPC is computational resource, and common errors in secure MPC include assuming semi honest behavior precluding collusions, input dependent flow, deterministic encryption and having a false notion of the absolute actions an adversary may take (rather than mathematical proof)..."*

**Our proposed architectures do not require any external party in the pipeline, yet achieving collaborative computing goals.**

[1]. Lindell, Yehuda, and Benny Pinkas. "Secure Multiparty Computation for Privacy-Preserving Data Mining." *Journal of Privacy and Confidentiality* 1.1 (2009).

# Strengths, Weaknesses and Future Directions



# Member Contributions

## Secure MPC



**Swapnil Sayan Saha**

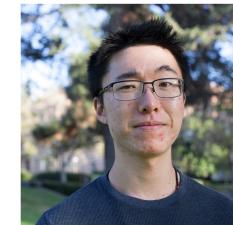
- Overseeing website/GitHub repo.
- Survey of literature pertinent to the fundamentals and latest advances in SMPC, with applications in MCPS.
- Implementation and preliminary benchmarking of basic SMPC protocols and custom oblivious functions in computer simulation.
- Implementation, dependency installation and benchmarking of SMPC protocols in Raspberry Pi hardware simulation environment.
- Tuning SMPC protocols for resource-constrained environments.

## Secure Aggregation



**Vivek Jain**

- Survey of literature pertinent to application of secure aggregation and SMPC for IoT sensor networks and MCPS
- Implementation and preliminary benchmarking of basic secure aggregation protocols and custom oblivious functions in computer simulation.
- Benchmarking secure aggregation protocols (in real-time) in Raspberry Pi environment and Mininet.
- Handling networking mechanisms in Mininet.
- Tuning secure aggregation protocols for resource-constrained environments.



**Brian Wang**

## Implementation

- Survey of literature pertinent to application of secure multiparty computation in medical cyberphysical systems and clinical decision support systems.
- Formulating SMPC and aggregation architecture for MCPS.
- Implementation of Mininet software simulation.
- Implementation and benchmarking (real-time) of SMPC and secure aggregation protocols in Mininet and Raspberry Pi.
- Handling networking mechanisms in Mininet and Raspberry Pi 4.

# THANK YOU

<https://github.com/swapnilsayansaha/BVSece209as>  
<https://swapnilsayansaha.github.io/BVSece209as/>