Leveraging Heterogeneous Programmable Data Planes for Security and Privacy of Cellular Networks, 5G & Beyond

JUNO-3 PI Meeting

April 3, 2023

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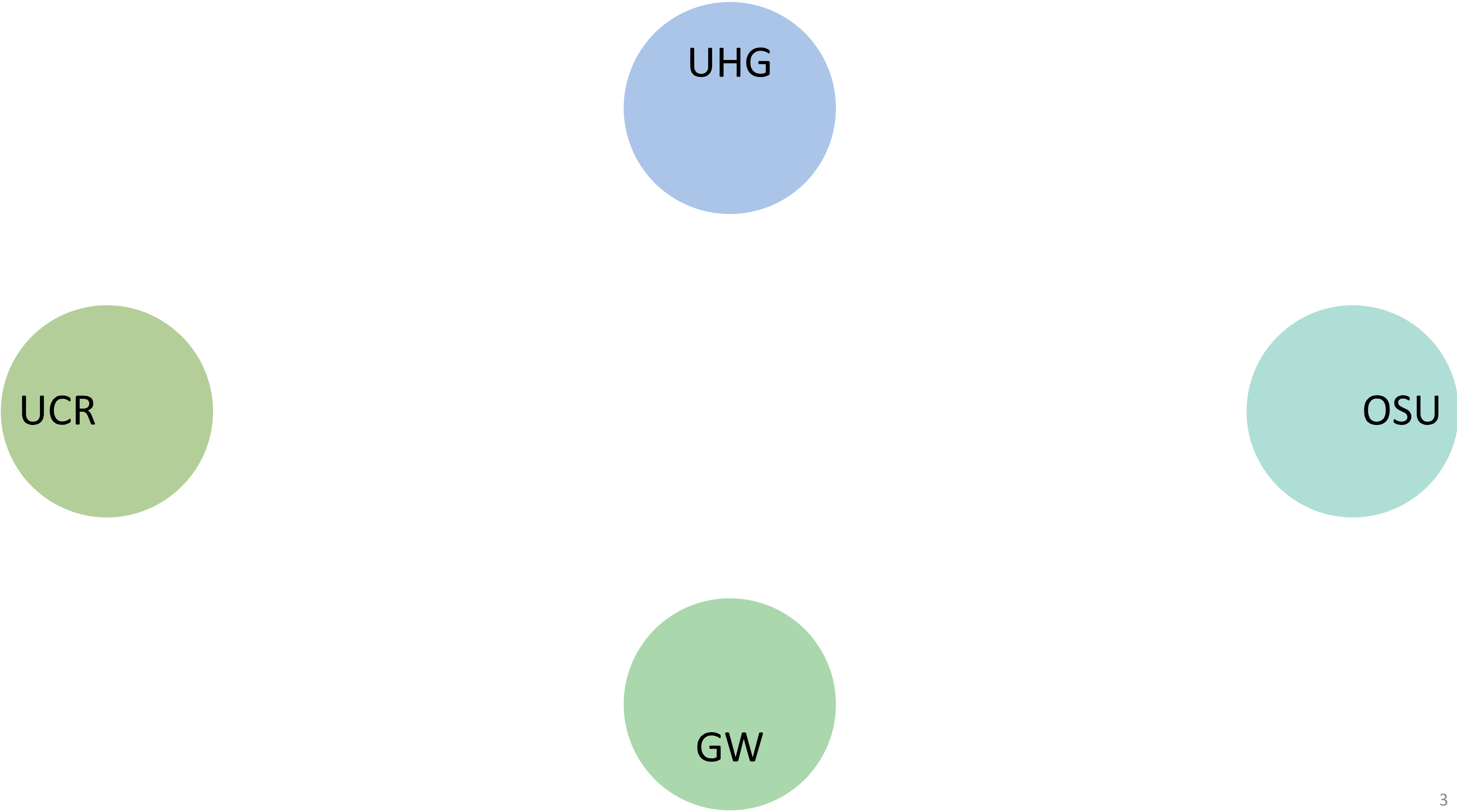
Importance of Programmable Data Planes for Cellular Performance & Security

- Cellular networks support a growing amount of traffic from mobile and Internet of Things (IoT) devices
  - Implementations moving to software-based environments: potential for increased vulnerability to security attacks, including violation of user privacy through eavesdropping
  - More slow and stealthy attacks: difficult to detect, need more memory and compute capacity
- Our project will use high speed programmable switches, SmartNICs and end-host servers supporting NFV to provide security monitoring and privacy protection solutions
  - Develop an efficient, high performance cellular network security solution
- Project builds on decade-long work on switching, SmartNIC and NFV work by PIs and collaboration between the PIs based in the US and Japan
- Monitoring: we will develop a collaborative filtering system for real-time monitoring of cellular traffic
  - Most of the traffic processed by high-speed programmable switches to extract coarse-grained metrics
  - Suspicious traffic redirected to programmable SmartNICs or the host for detailed forensics
- Privacy Protection: utilize P4 programmable switches for anonymization and privacy protection
  - Lightweight Anonymization at Terabit rates within the network layer with high-speed P4 switches
  - Use traffic morphing to handle fingerprinting attacks
- Societal Impact: Provide strong threat prevention and privacy preservation of cellular network users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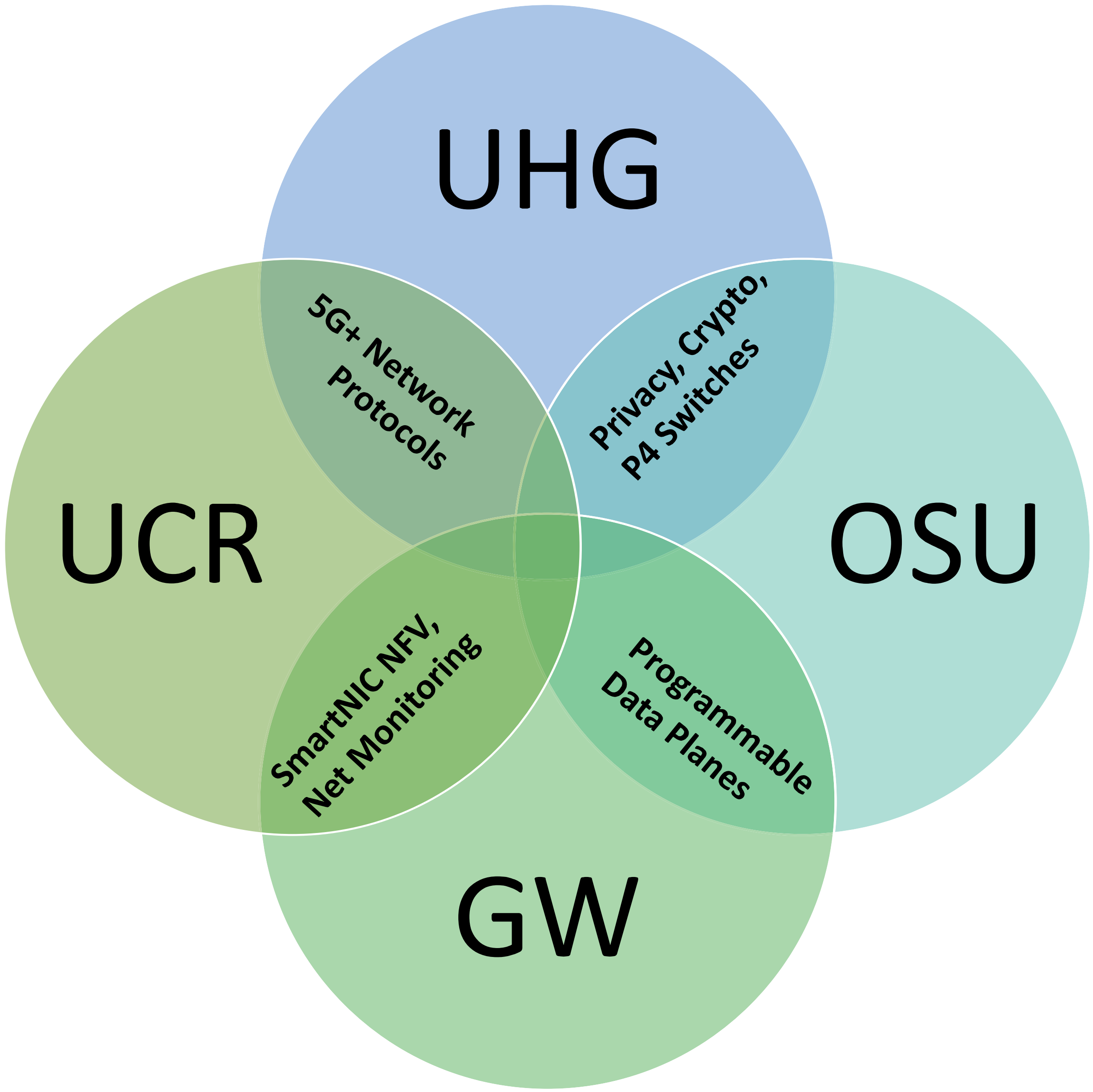
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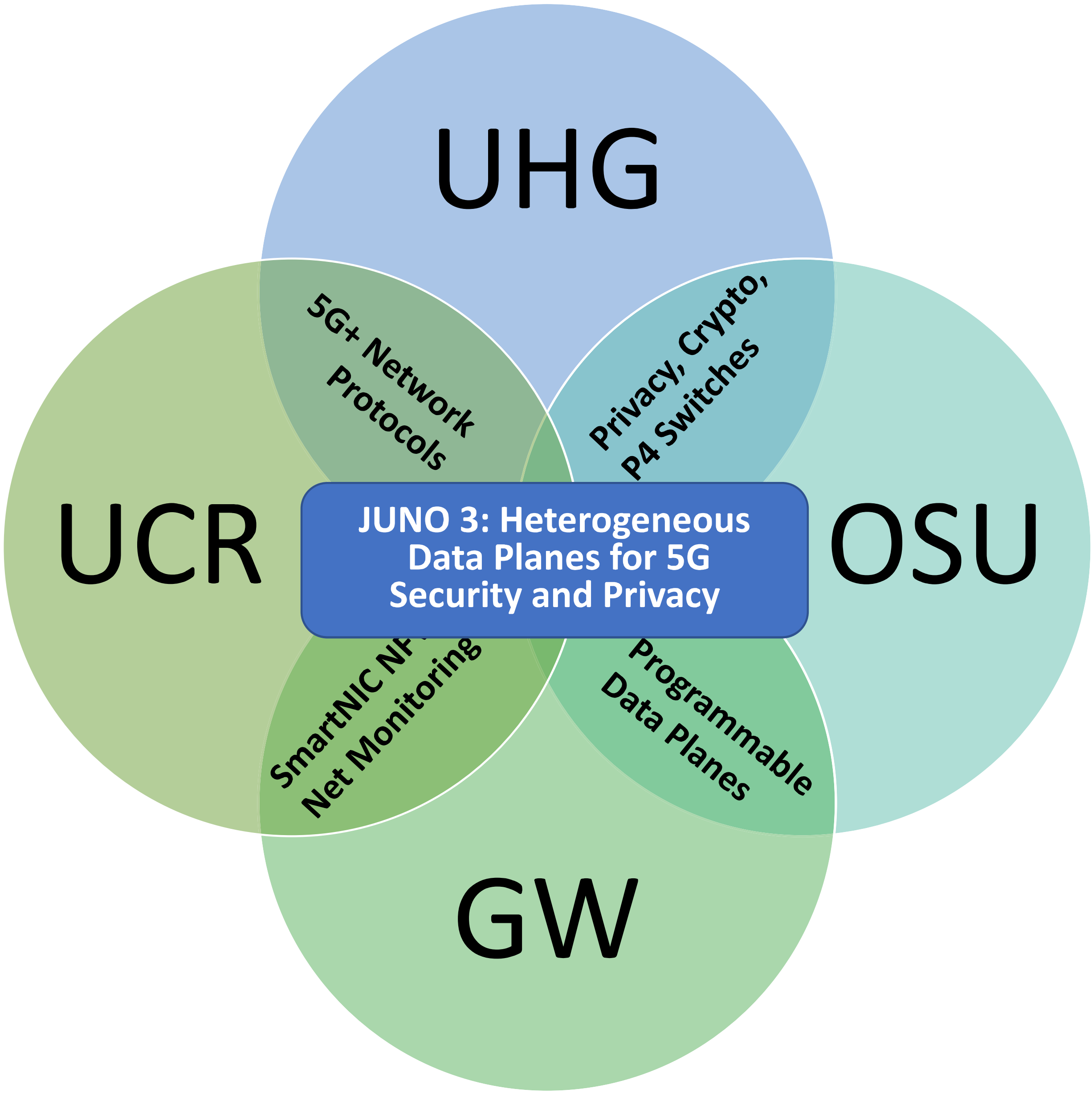
5G+ Network Protocols
Privacy, Crypto, P4 Switches
SmartNIC NFV, Net Monitoring
Programmable Data Planes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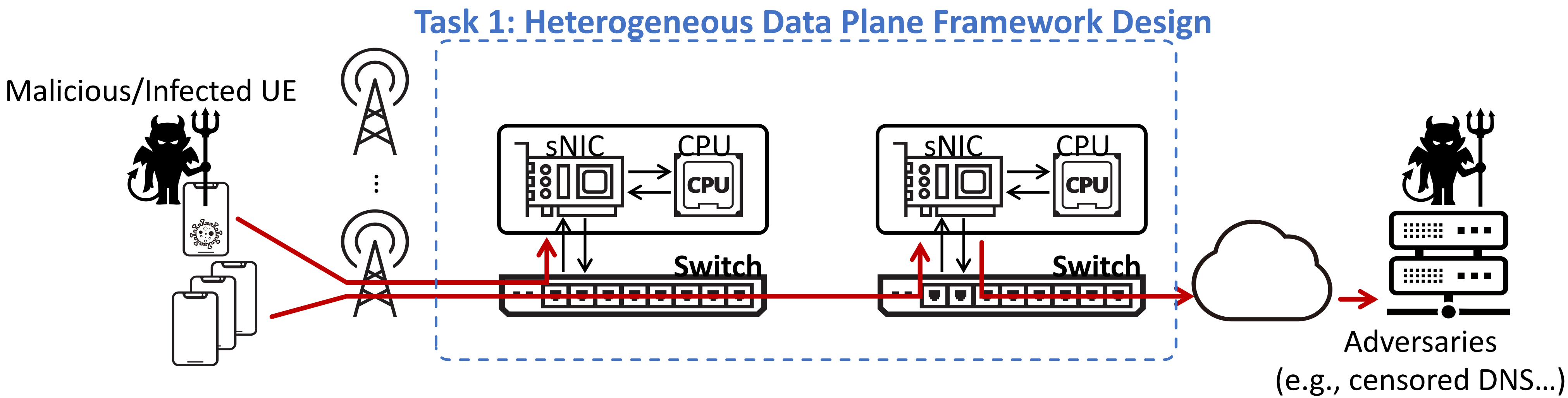
Programmable Data Planes
JUNO 3: Heterogeneous Data Planes for 5G Security and Privacy

Overview of Proposed work

Task 1: Heterogeneous Data Plane Framework

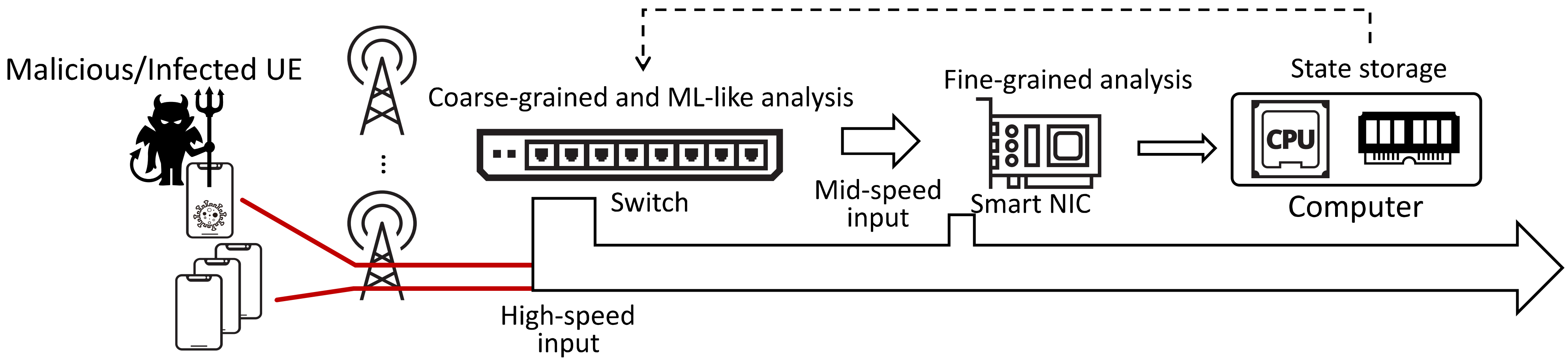


- Design a programmable data plane framework to leverage heterogeneity:
  - P4 Switches: High bandwidth (Tbps), limited memory (MBs)/programmability
  - SmartNICs: Moderate bandwidth (Gbps), moderate memory (GBs); Programmable
  - Host CPUs: Limited bandwidth, large memory (TBs), general purpose CPUs

Task 1: Heterogeneous Data Plane Framework

- Goal:
  - Coordinate protocols between various programmable network devices to overcome their limitations while optimizing their strengths
- Key techniques
  - **Cooperative flow filtering** and state caching across heterogeneous programmable network devices
  - **In-network ML inference:** get high throughput by using the pipelined processing of packets on P4 switches and slicing of GPUs on hosts
  - **Optimization algorithms** that use models of component capabilities to effectively determine which traffic monitoring modules to place on which types of data plane hardware

Task 2: Real-time Network Monitoring

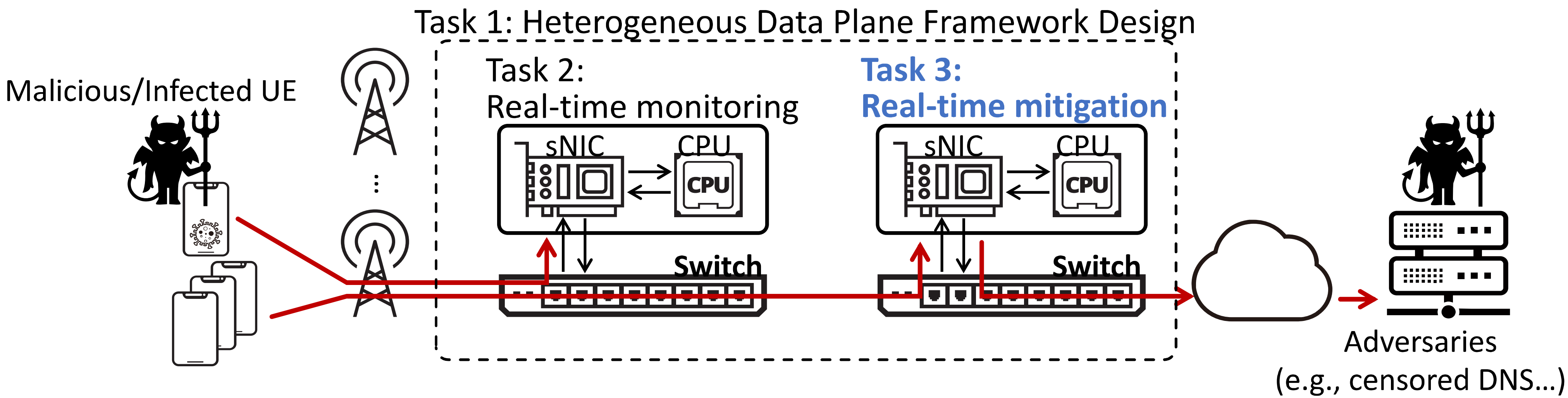


- Use heterogeneous data plane for real-time monitoring of 5G networks
  - 5G core based on multi-tier programmable data and control plane components
  - Line rate traffic monitoring for 5G resource management and anomaly detection

Task 2: Real-time Network Monitoring

- Goal: Leverage programmable dataplane at base stations and 5G core to enable real-time monitoring and security
- Applications:
  - **Resource management and mobility prediction** through analysis of control and data plane traffic in 5G core
  - **Protecting UEs** from both volumetric and slow attacks through UPF-based monitoring of control and data planes
  - **Securing 5G infrastructure** from rogue UEs and gNBs by aggregating monitoring data across devices

Task 3: Real-time Privacy Preservation/Attack Mitigation

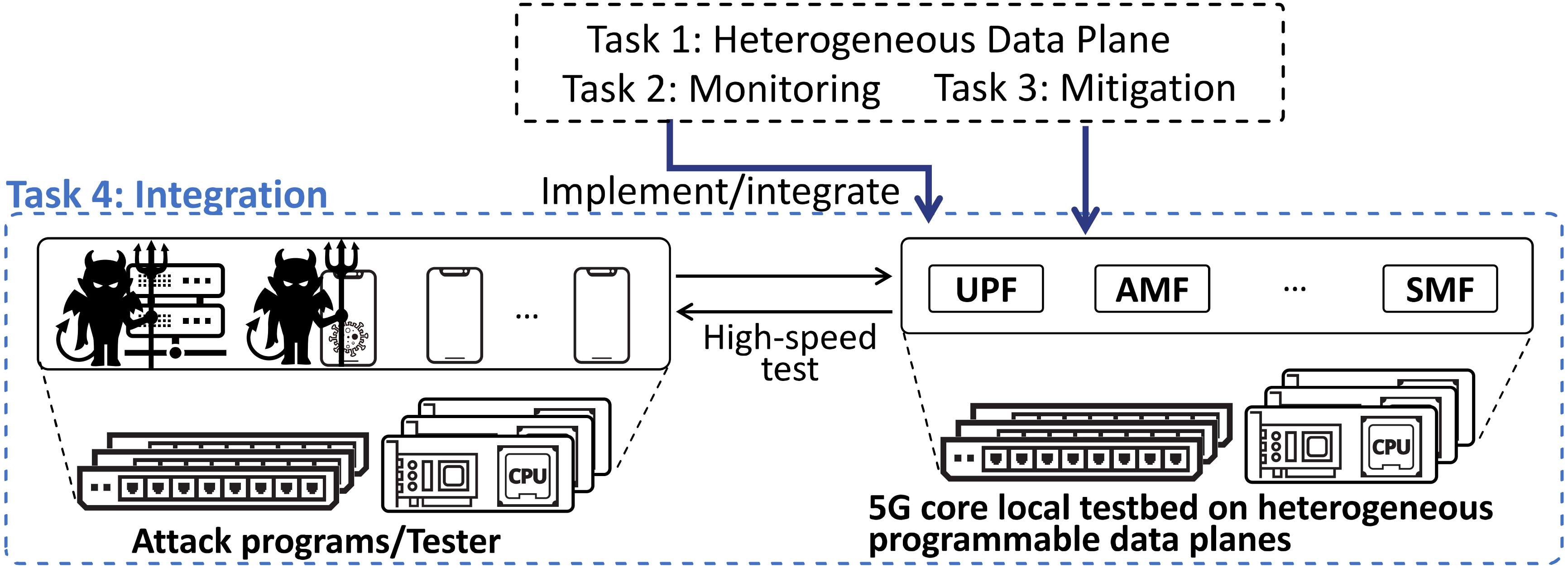


- Prevent attacks and preserve privacy for mobile users
  - Lightweight traffic encryption protocols to provide relationship anonymity
  - Traffic obfuscation techniques to prevent fingerprinting attacks

Task 3: Real-time Privacy Preservation/Attack Mitigation

- Goal: Privacy protection for users who access Web sites and various data
- Key techniques
  - **IP address obfuscation** through light weight anonymous routing protocol at the network layer and its implementation on a P4 switch
  - **Traffic morphing** to prevent fingerprinting attacks by inserting dummy packets and data
  - **DNS privacy protection** with a novel distributed and multiple-hop based approach of anonymization technique on DNS queries, and its design and implementation of its 'lite-version' on P4 switch

Task 4: Integration



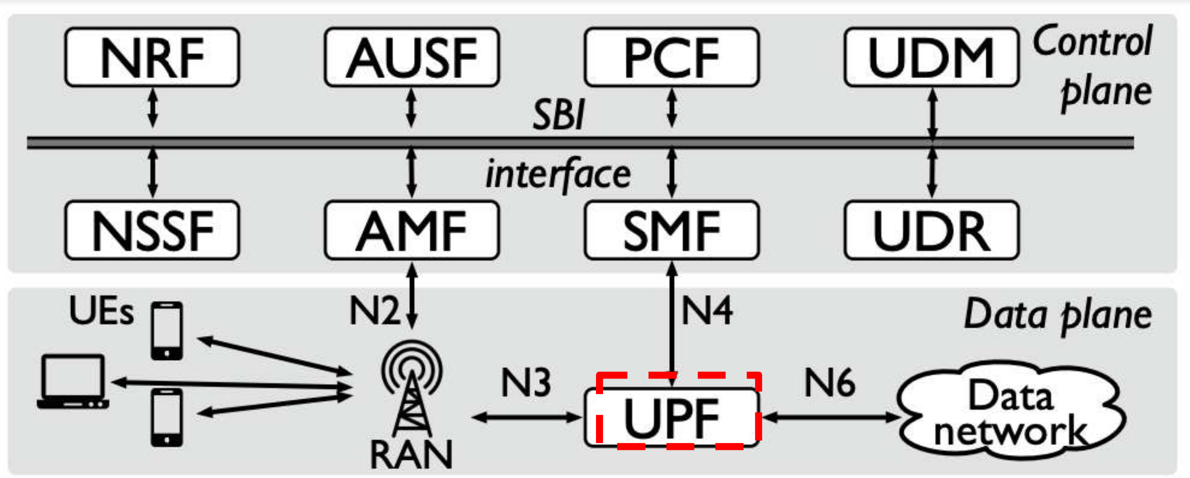
- Deploy a holistic system to study security and performance properties
  - Evaluate traffic monitoring and privacy preservation techniques on 5G testbed
  - Optimize the combination of hosts, P4 switches, and SmartNICs

Sample Projects

1. SmartNIC Accelerated Traffic Monitoring in the Cellular Core
2. Lightweight Anonymity Protocols for P4 Switches

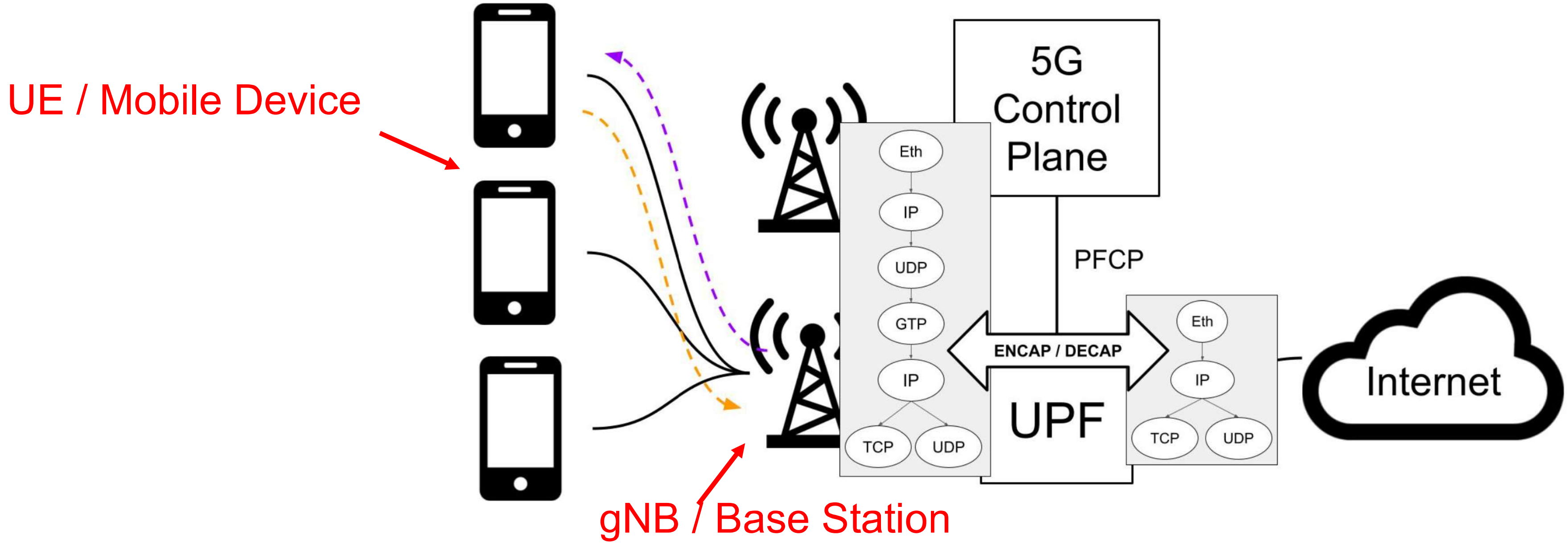
Synergy: Traffic Monitoring in the Cellular Core

- 5G Core (5GC) is the heart of a 5G mobile network
  - Establishes reliable, secure connectivity to network for end users
  - Mobility management, authentication/authorization, and policy management
- The 5GC is comprised of several control plane and dataplane NFs.
- The User Plane Function (UPF) is the primary dataplane component of the 5GC



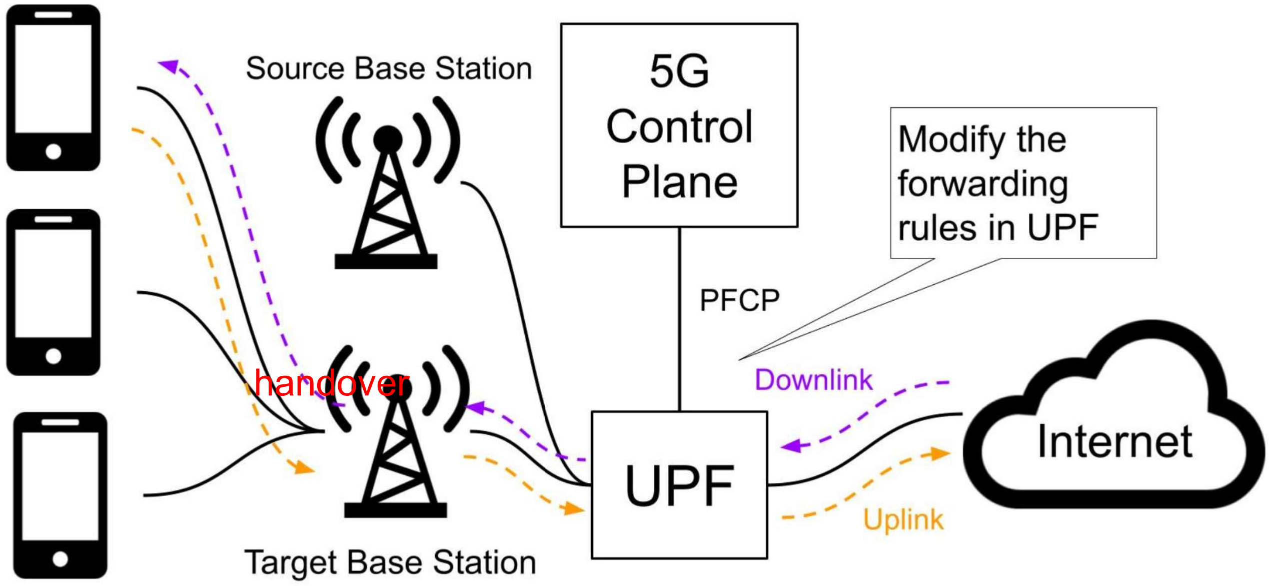
User Plane Function (UPF) : The 5G Dataplane

- Interconnect point between the mobile infrastructure and the data network.
- Implements complex rules for forwarding and tunneling.
  - Processes packets belonging to different sessions , priorities, including shaping and policing.
  - Must have high throughput and low latency→ spurious retransmissions and also packet loss.



UPF: Perform flow-state dependent processing

- Has to be aware of the idle and active transitions (Paging) → Save energy.
- Radio association change from one base station to another → Mobility.
- Lots of protocol msg exchanges that change the dataplane
  - Change must be affected quickly → Packets can be forwarded

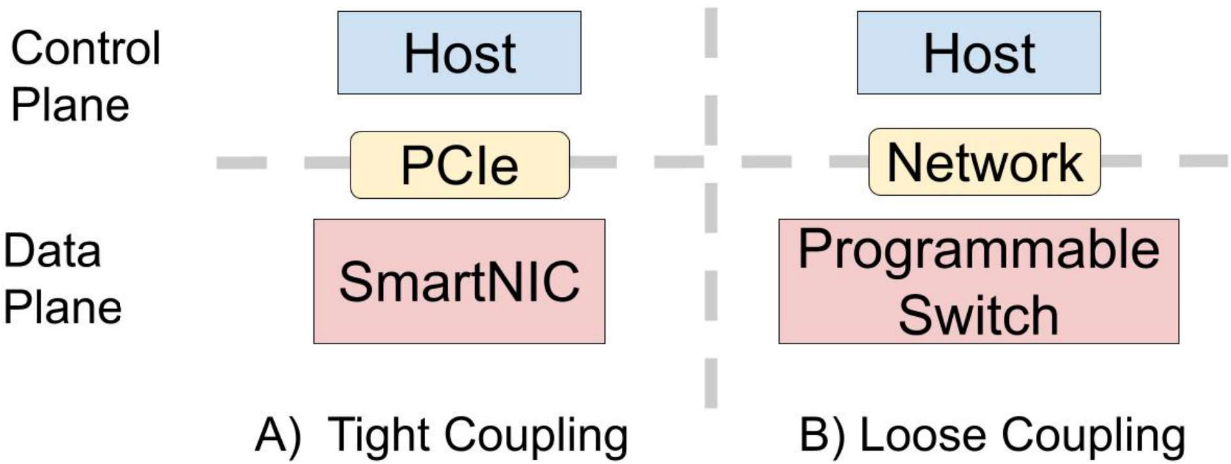


Improving Control/Data Plane throughput and latency

Require programmability: Rules have to be rapidly and frequently modified

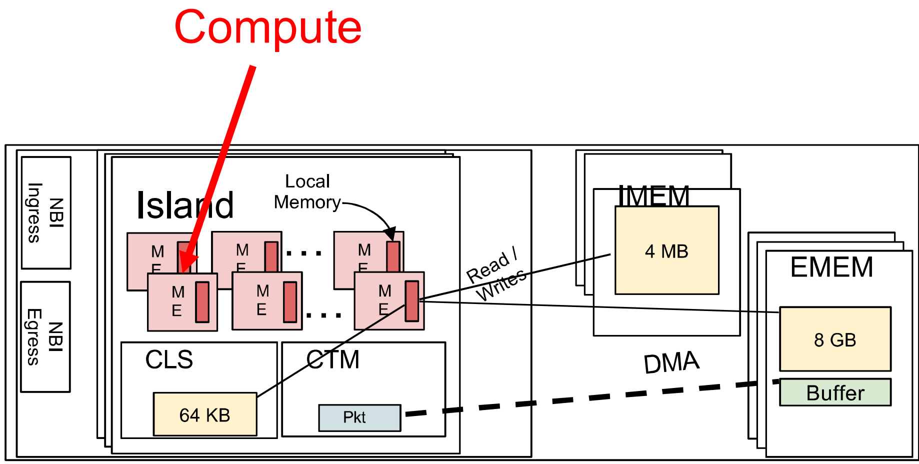
- Rules change when mobile device goes through handover, attach/detach, idle-active transition.
- Programmability of the SmartNIC can be tremendous advantage
- Take advantage of the tight coupling by using a SmartNIC accelerator.

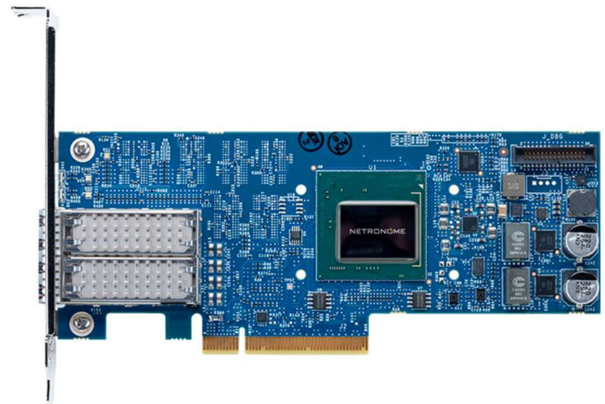
- **With a performant UPF, we can now enhance functionality: monitor the network; mobility prediction**
  - Prepopulate the state in 5GC to accelerate the control plane event → **Quicker handover.**
  - Enabler: Monitor control plane traffic in the SmartNIC → Predict Mobility → Prepopulate State



Synergy: P4 Programmable SmartNICs Primer

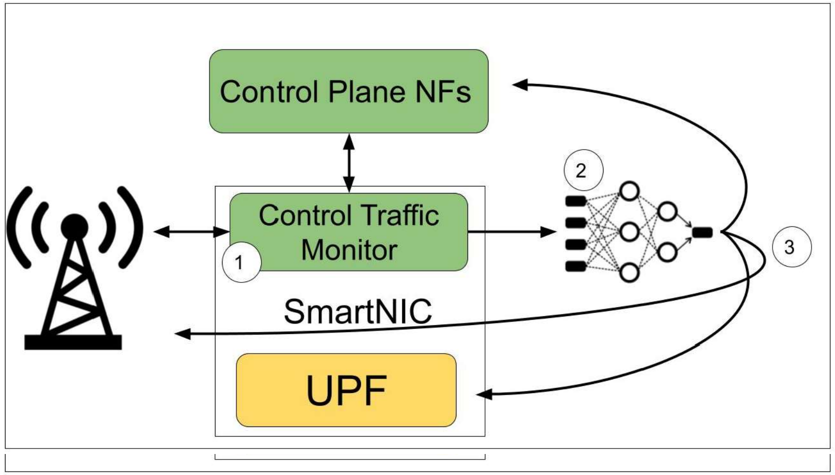
- We implemented Synergy on a Netronome Agilio LX 2x40GbE.
- 96 P4/ Micro-C programmable flow processing cores
  - Parallelism for packet forwarding processing.
- Memory Hierarchy (SRAM + DRAM)
  - Large memories (DRAM), slow to access → Buffering.
  - Smaller memories, bounded access latency → Forwarding.
- Dynamically push rules into the SmartNIC
  - Pushing rules in response to handovers / paging.
  - Takes advantage of the tight coupling with the host



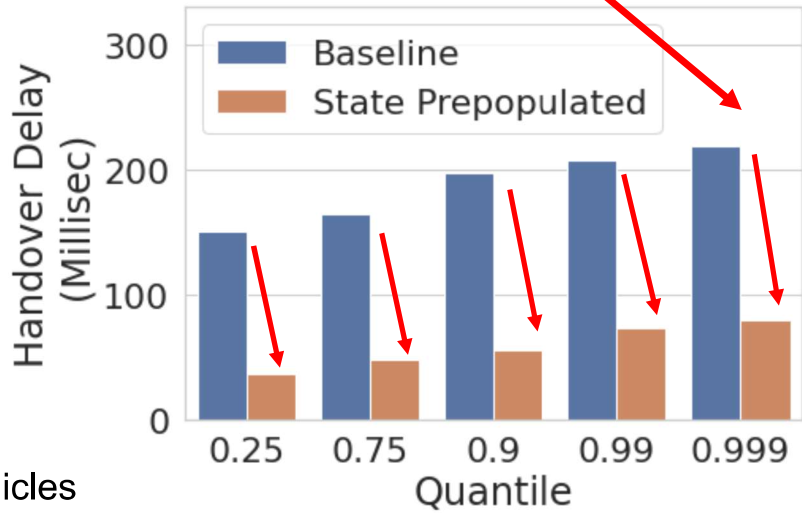


Application - Monitoring and Mobility prediction

- Carryout monitoring in the SmartNIC to do mobility predictions.
- Input: Mobile Device's Location report that the AMF requests; Output: UE's next base station.
- Model: Recurrent neural network model [1]
- **SUMO-based vehicular mobility dataset:**
  - 700k vehicle trips across 247 gNBs. [2]
  - At each point in time, the UE connects with the gNB providing the best communication conditions, measured in terms of path loss.



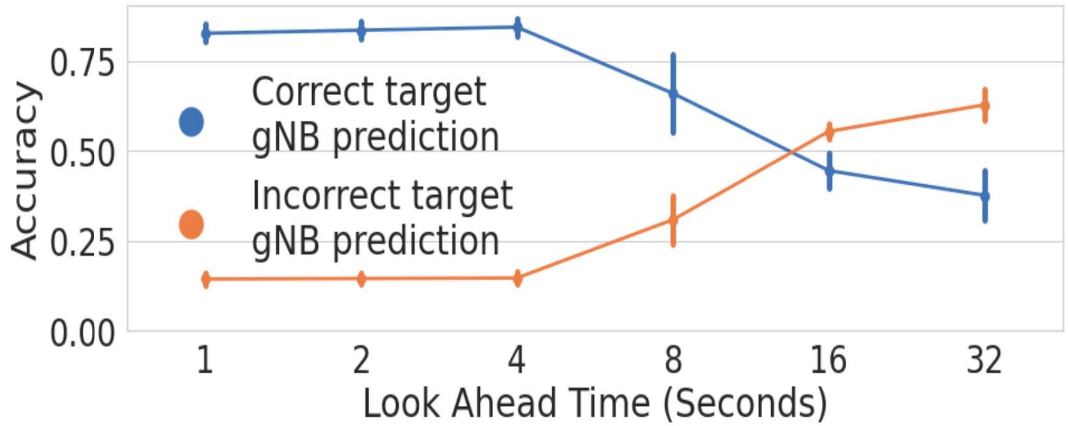
Benefit of state pre-population

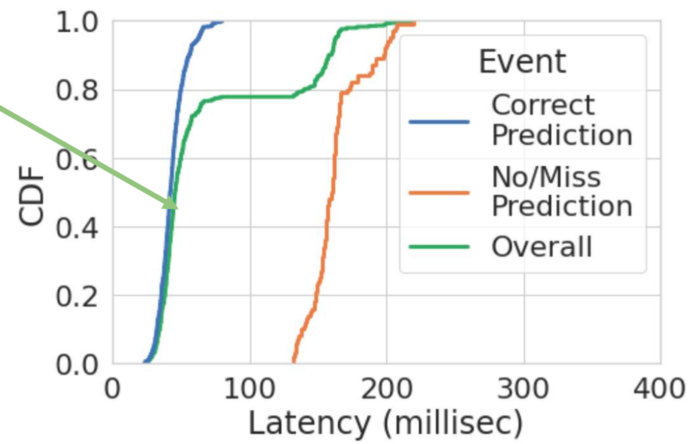


[1] Mobility aware and dynamic migration of MEC services for the internet of vehicles
[2] ttp://kolntrace.project.citi-lab.fr/

Benefit of Mobility Prediction and Tight coupling

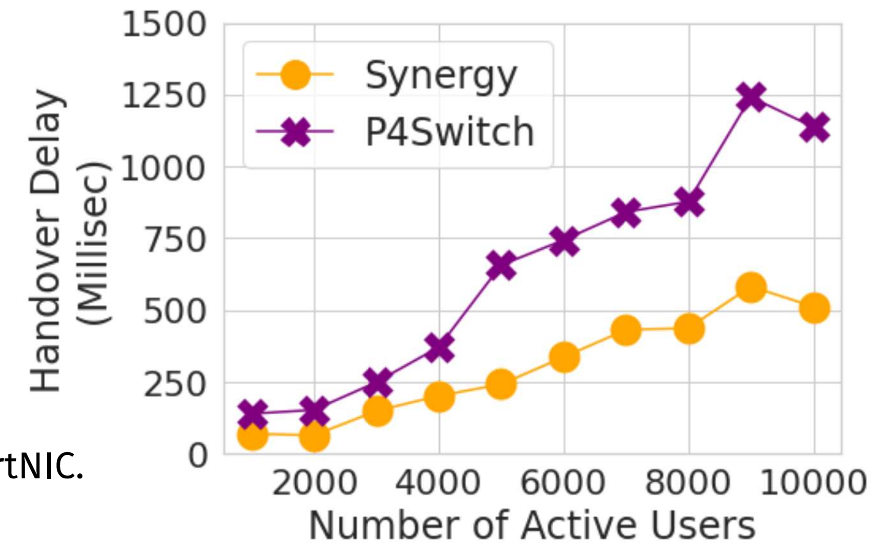
- Not possible to always have correct predictions
- Predict mobility with lookahead ~5 sec
  - Lookahead > 5 sec: Poor accuracy
  - Lookahead < 5 sec: Too many predictions
- Correct predictions reduce handover delays





Benefit of Mobility Prediction and Tight coupling

- Low programming latency → Lower Handover Delays
- Programmable Switches have been emulated here.
- Constraint with Programmable Switch: ~1200 rules/sec[1]



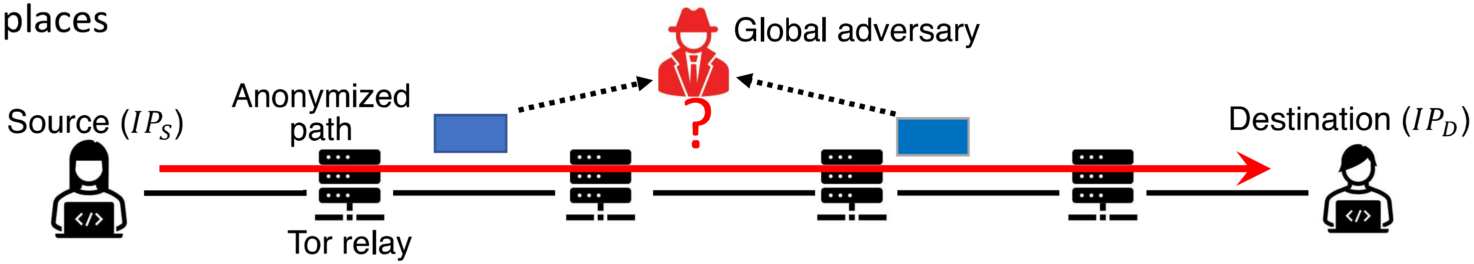
Summary

- Synergy accelerates the UPF throughput and reduces latency with the SmartNIC.
- SmartNIC-based UPF buffers packets:
  - Speed up control-to-data plane interaction
  - Reduces the impact on Handovers and Paging
- Handover latency reduced by monitoring and mobility prediction to prepopulate state.

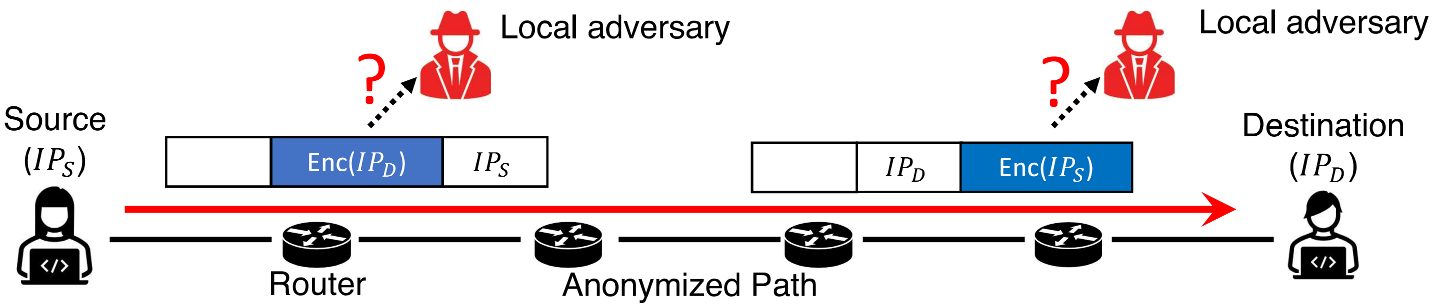
[1] NetWarden: Mitigating network covert channels while preserving performance (NDSS’20)

Background: Tor vs. Lightweight Anonymity Protocol in the Network Layer

- Tor assumes global adversary
  - Tor relays encrypt both headers and payloads to prevent a global adversary from correlating packets intercepted at multiple places



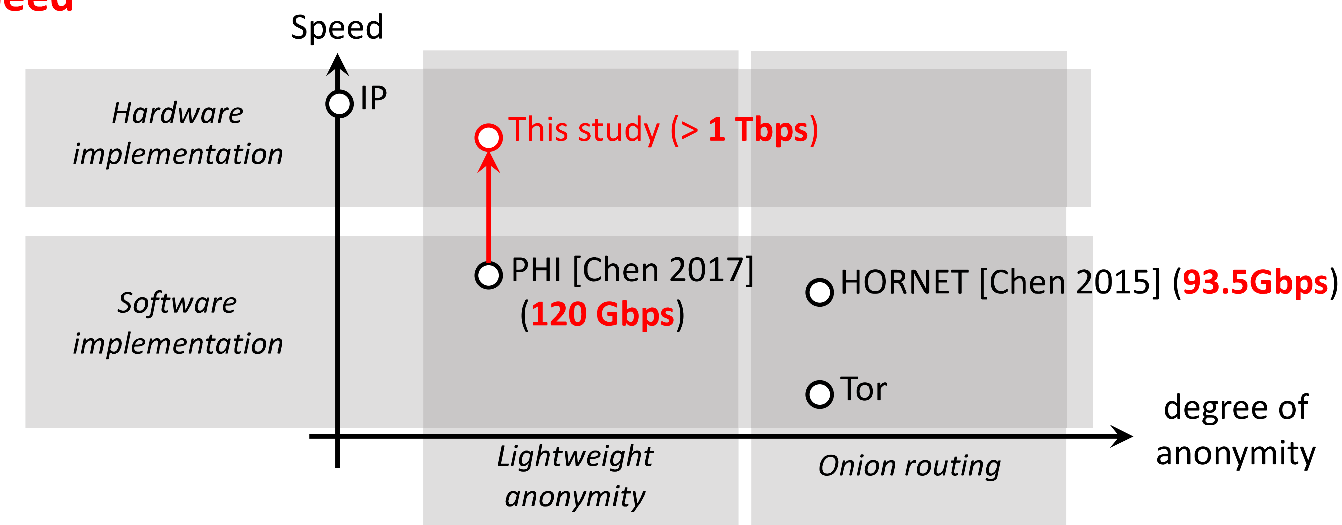
- Lightweight anonymity protocol assumes weak adversary
  - Routers obscure either source or destination address to prevent a local adversary from correlating source and destination addresses from packets intercepted at one place (relationship anonymity)
  - Advantages
    - High-speed forwarding owing to encryption of only headers
    - Short path length owing to the underlying IP routing path



[4] Yutaro Yoshinaka, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, "Design and analysis of lightweight anonymity protocol for host- and AS-level anonymity ," Computer Networks, Volume 222, 109559-109559, Feb. 2023.

Problems and Goals

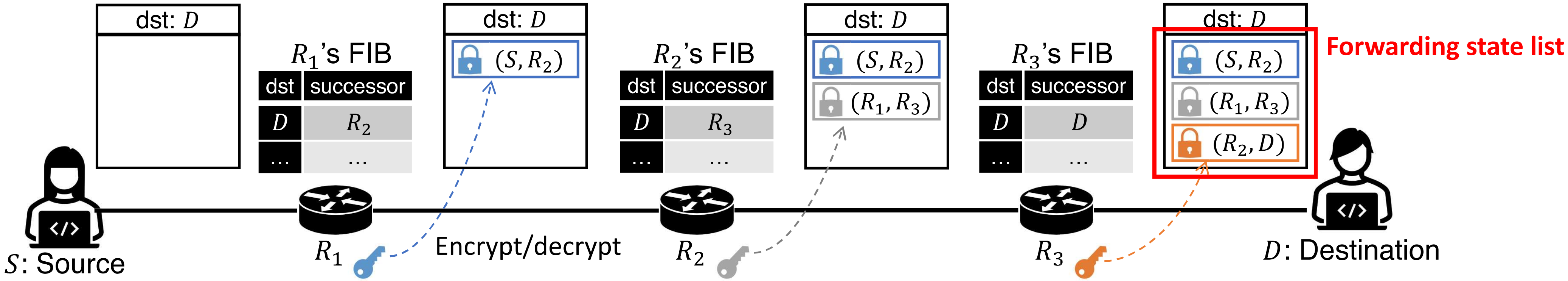
- Problems
  - Existing implementations only target **software switches**
    - Terabit speed, required for backbone routers, is unachievable on software switches
      - PHI [Chen 2017] achieves **120Gbps**
      - HORNET [Chen 2015], a protocol performing onion routing, achieves **93.5Gbps**
- Goals
  - Implementing lightweight anonymity protocols on **programmable switches** for anonymous communication at **terabit-class speed**



[Chen 2017] Chen, Chen, and Adrian Perrig. "PHI: Path-hidden lightweight anonymity protocol at network layer." *Proc. Priv. Enhancing Technol.* 2017.1 (2017): 100-117.
[Chen 2015] Chen, Chen, et al. "HORNET: High-speed onion routing at the network layer." Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security. 2015.

Lightweight Anonymity Protocol (AP)

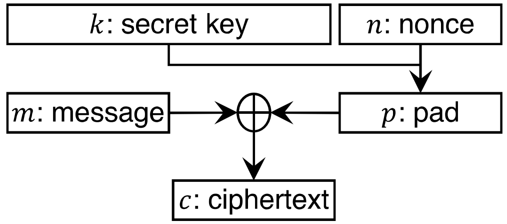
- Path setup phase
  - Routers create a forwarding state list in the onward trip to the destination
    - Pairs of predecessor and successor information (forwarding states) determined by IP routing
    - Encrypted with routers' secret keys and stored in packet headers
  - Destination replies with completed forwarding state list in the return trip



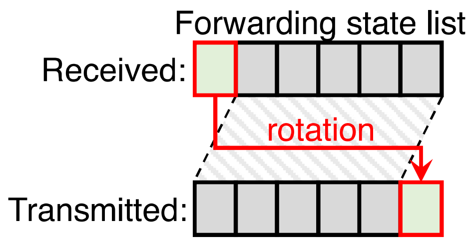
- Data transmission phase
  - Forwarding state list is recorded in packet headers
  - Routers retrieve and decrypt their own forwarding state for forwarding
  - Routers are stateless (states are kept in packet headers)

Design Challenges and Solutions

1. Cryptosystem
   - It must be able to be executed by a **limited instruction set** and a **limited number of stages**
   - Solution: **One-time pad cipher**
     - Suitable for encrypting on switches because encryption and decryption are equivalent
     - Half SipHash (keyed hash function) only uses addition, XOR, and bit rotation



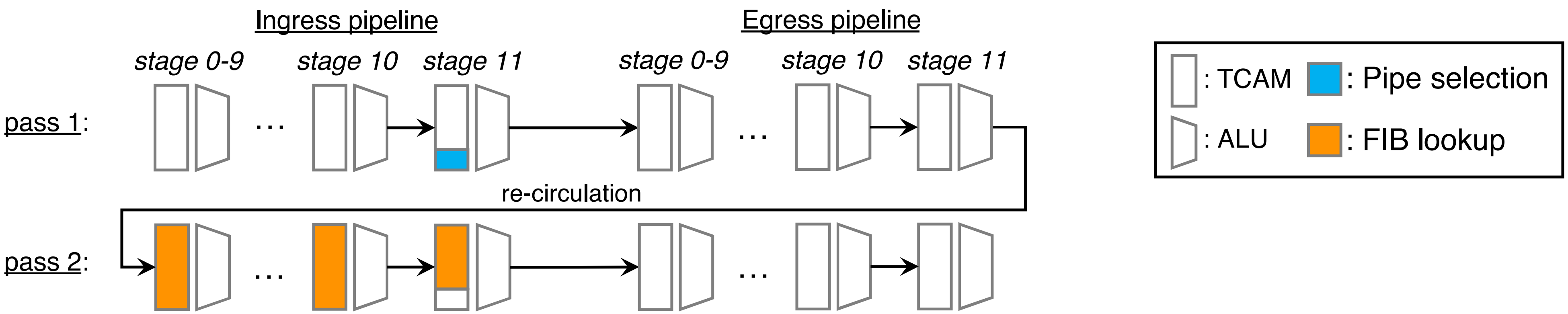
2. Data structure for accommodating a forwarding state list
   - It must satisfy anonymity requirements (e.g., **not leaking length of path**) and must be **lightweight to process** and not require extra computation
   - Solution: Rotatable array
     - The forwarding state list is **rotated after accessed**



3. IP routing support
   - It must handle **normal IP packets** as well for incremental deployment
   - It must keep **IPv4 full route** (500K entries)
4. Layout of the program on the switch's pipeline
   - Must implement the above functions with satisfying **Tofino's constraints**
   - Must minimize the number of recirculations for **terabit-class speed forwarding**

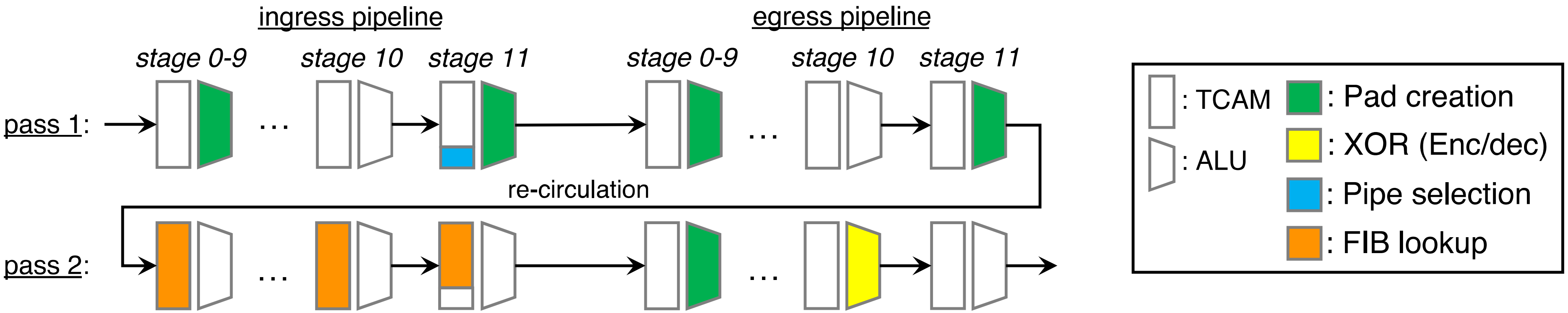
Layout of the Program on Switch Pipeline

- Layout constraints
  - A switch ASIC has 2 12-stage pipelines (ingress and egress pipeline)
  - Generating a one-time pad requires **32 stages**
  - Looking up FIB requires **12 stages**
  - Egress ports must be determined in the **ingress pipeline**
- Resulting Layout: We implement the functions with **one recirculation**
  - IP packet processing

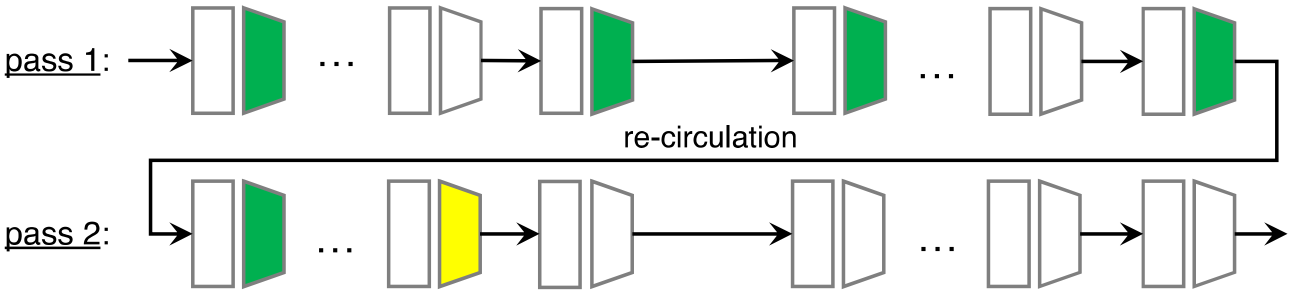


Layout of the Program on Switch Pipeline

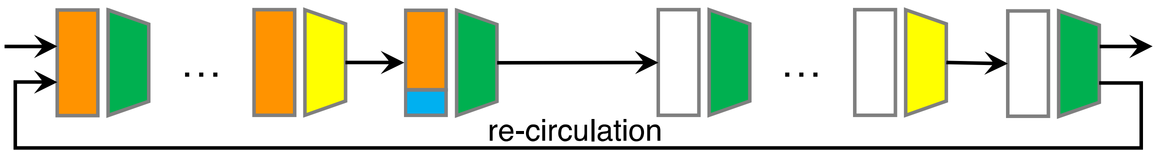
- Anonymity packet processing (path setup phase: encryption)



- Anonymity packet processing (data transmission phase: decryption

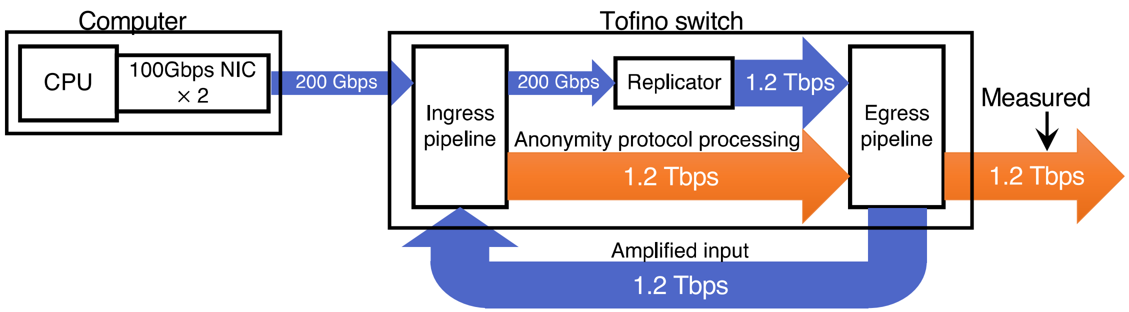


- Integrated pipeline layout

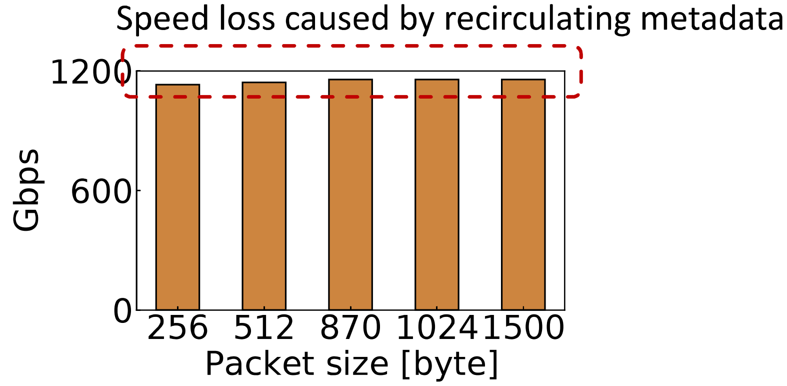


Evaluation and Future Directions

- Evaluation method
  - We implement designed pipeline using a Tofino switch (Wedge 100BF-32X **32 100 Gbps ports**)
  - Ideal forwarding speed is **1.2 Tbps**
    - 200 Gbps traffic is injected and amplified six times inside the switch
  - 2 ports are used for input, 12 are used for recirculation, and 12 are used for output
- Result: 1.16 Tbps forwarding speed



Experiment setup

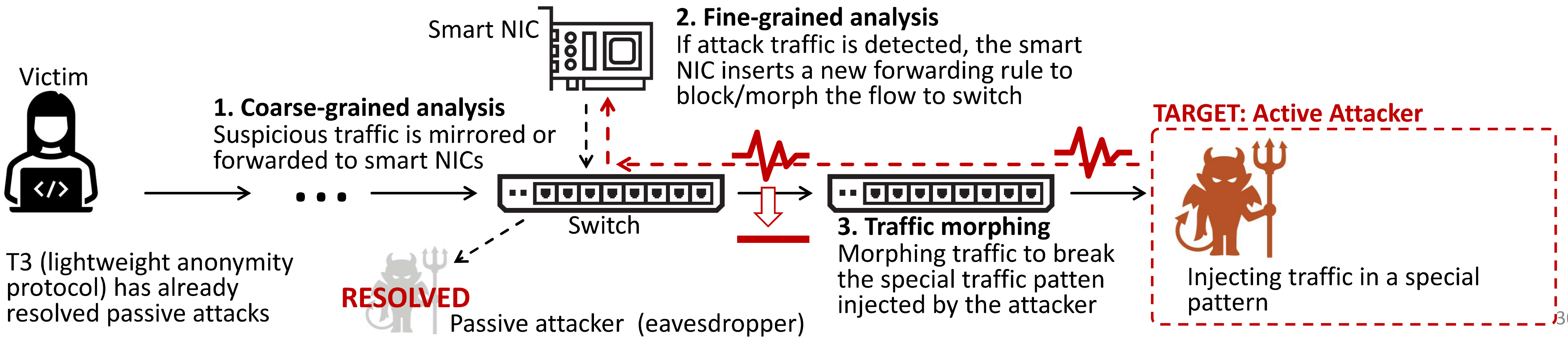


Forwarding speed result

- Ongoing research
  - Message authentication code (MAC) generation/verification **against attacks on path integrity**
  - **Stronger cryptosystem** like one-time pad with ShipHash instead of Half SipHash
- **Future research plan:**
  - **Smart NICs and switches for collaborative mitigation against active attacks**

Collaborative Smart NIC/Switch Secure and High-speed Anonymity Protocol

- Background: Anonymity protocols are **weak against active attacks**
  - Attackers can identify that a victim uses a certain router for anonymous communication
    - Injecting traffic in special patterns (like periodic bursts) toward the victim
    - Probing the perturbation caused by the injected traffic
- Approach: Smart NICs and switches collaboratively monitor and prevent the active attacks
  - Programmable switches
    - Coarse-grained analysis of active attacks
    - Traffic morphing to mitigate the attack
  - Smart NICs
    - High-speed and fine-grained monitoring of active attacks against anonymity protocol



Dissemination of Project Achievements: Summary

- We are designing the architecture to publish a joint paper
- Publications so far:

1. Kentaro Kita, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, “Secure Middlebox Channel over TLS and its Resiliency against Middlebox Compromise,” in Proceedings of IEEE INFOCOM 2023, May 2023.
2. Cuidi Wei, Ahan Kak, Nakjung Choi, and Timothy Wood, “Towards a Scalable 5G RAN Central Unit,” in Proceedings IEEE INFOCOM 2023 Workshop on Next-generation Open and Programmable Radio Access Networks (NG-OPERA), May 2023
3. Ryu Watanabe, Ayumu Kubota, and Jun Kurihara, "Application of Generalized Deduplication Techniques in Edge Computing Environments," to Appear in Proceedings of AINA 2023 (M2EC-2023), Juiz de Fora, Brazil, Mar. 2023.
4. Yutaro Yoshinaka, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, “Design and analysis of lightweight anonymity protocol for host- and AS-level anonymity ,” Computer Networks, Volume 222, 109559-109559, Feb. 2023.
5. S. Panda, K. K. Ramakrishnan and L. N. Bhuyan, "Synergy: A SmartNIC Accelerated 5G Dataplane and Monitor for Mobility Prediction," *2022 IEEE 30th International Conference on Network Protocols (ICNP)*, Lexington, KY, USA, 2022.

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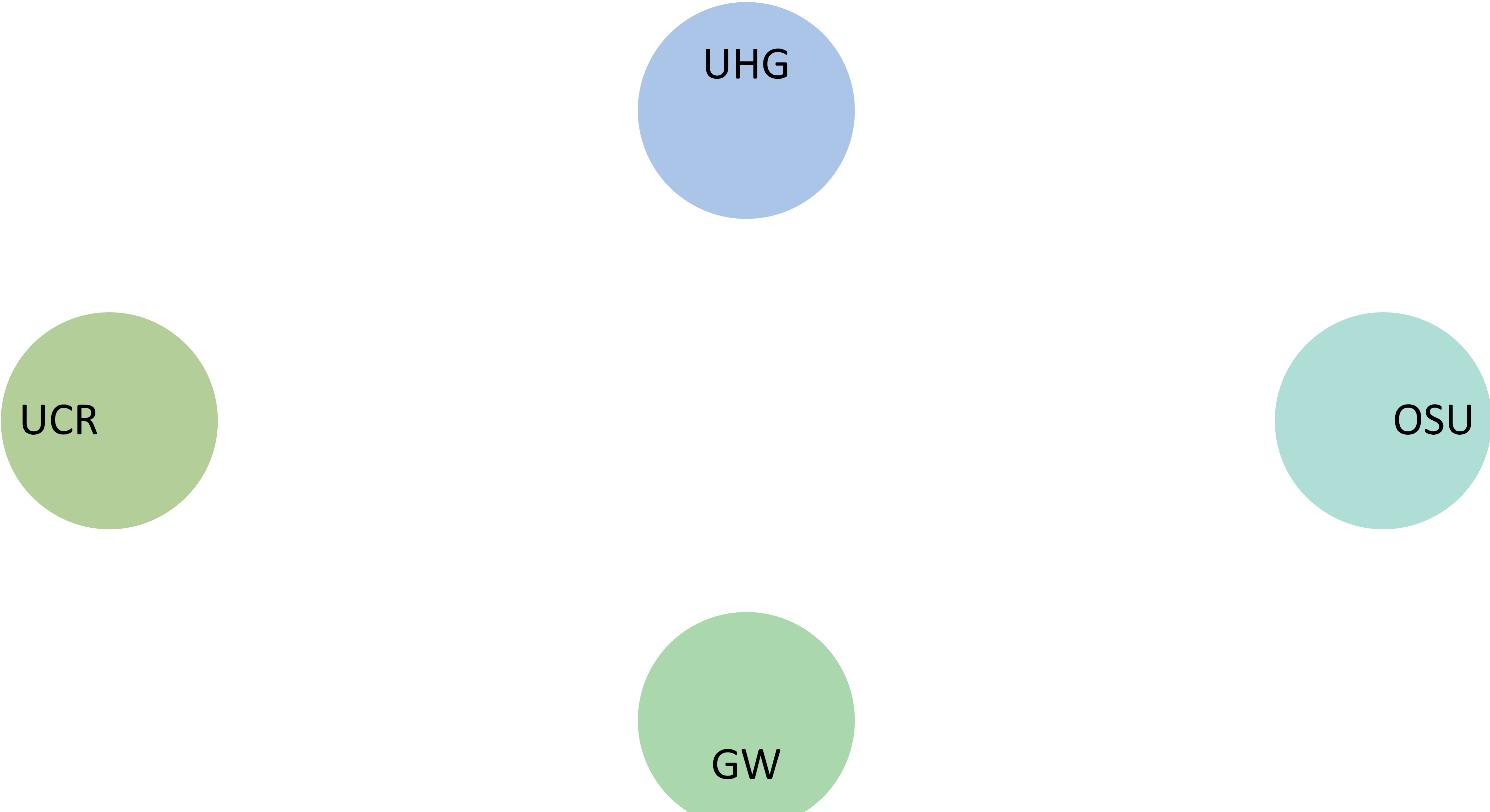
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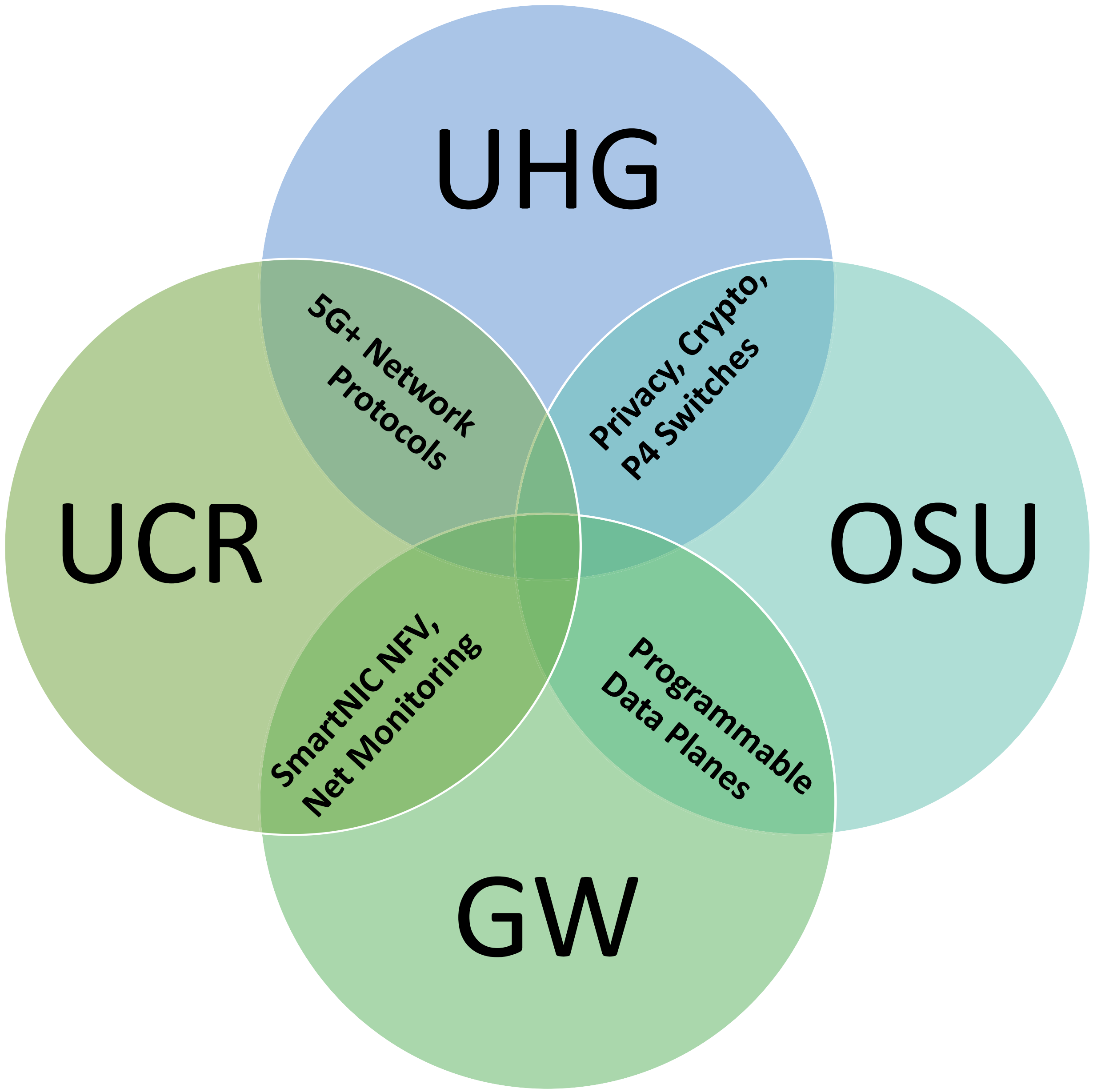
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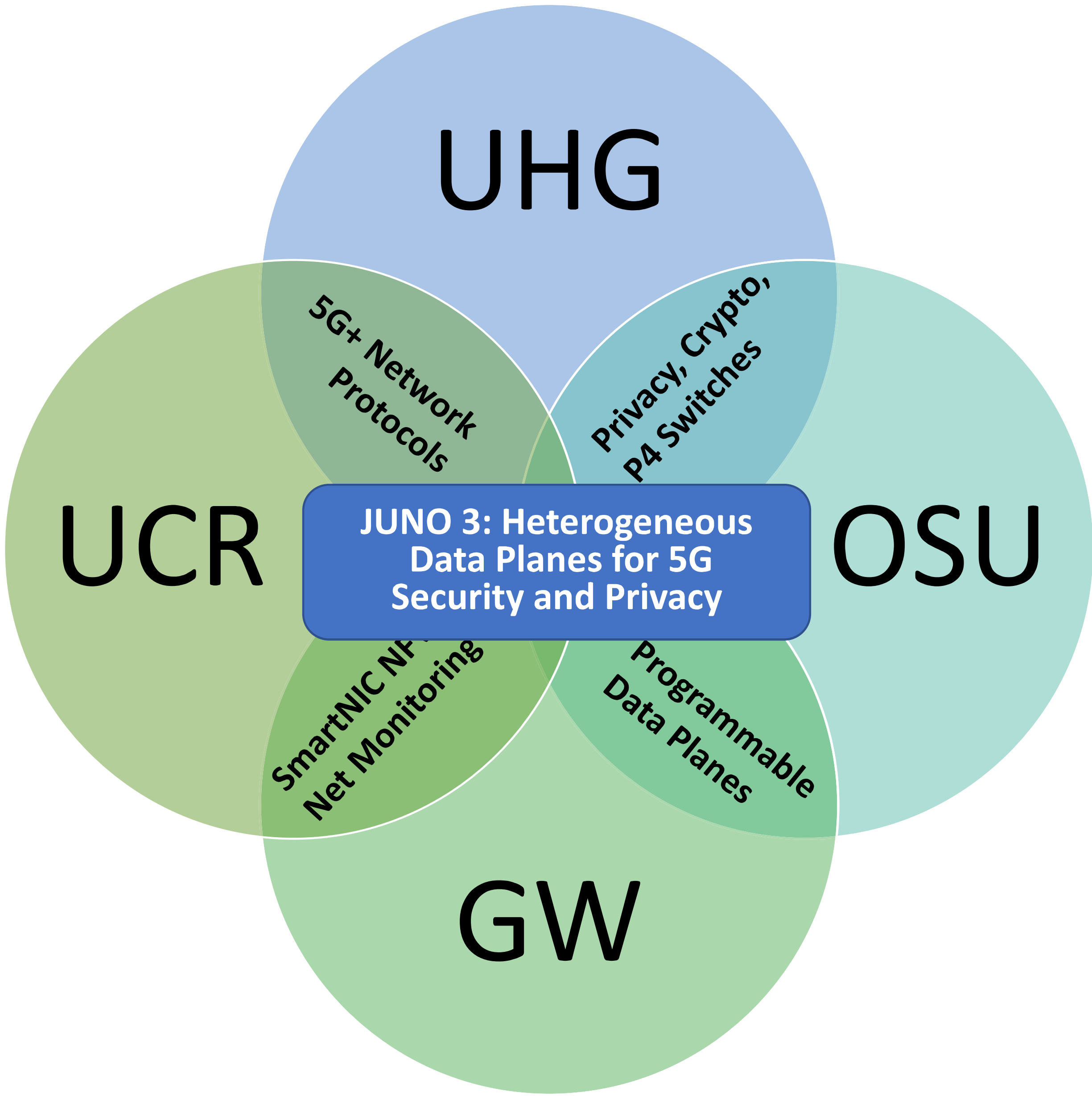
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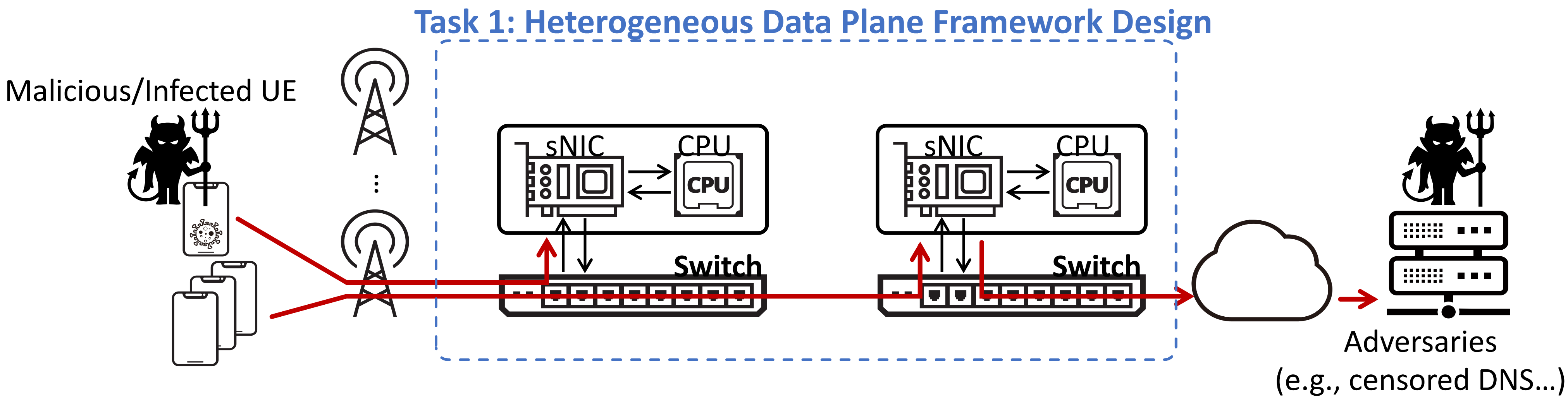
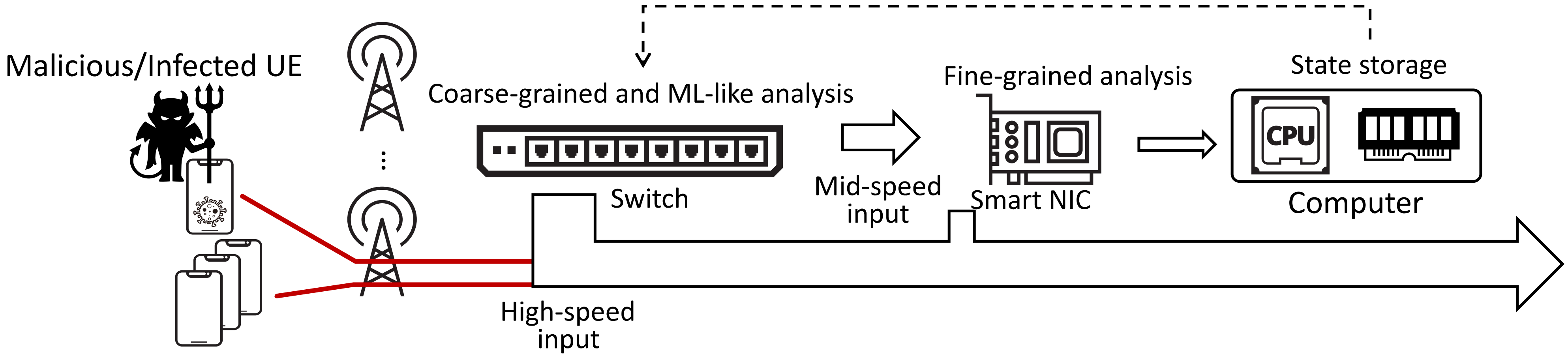


- Design a programmable data plane framework to leverage heterogeneity:
  - P4 Switches: High bandwidth (Tbps), limited memory (MBs)/programmability
  - SmartNICs: Moderate bandwidth (Gbps), moderate memory (GBs); Programmable
  - Host CPUs: Limited bandwidth, large memory (TBs), general purpose CPUs

Task 1: Heterogeneous Data Plane Framework

- Goal:
  - Coordinate protocols between various programmable network devices to overcome their limitations while optimizing their strengths
- Key techniques
  - **Cooperative flow filtering** and state caching across heterogeneous programmable network devices
  - **In-network ML inference:** get high throughput by using the pipelined processing of packets on P4 switches and slicing of GPUs on hosts
  - **Optimization algorithms** that use models of component capabilities to effectively determine which traffic monitoring modules to place on which types of data plane hardware

Task 2: Real-time Network Monitoring

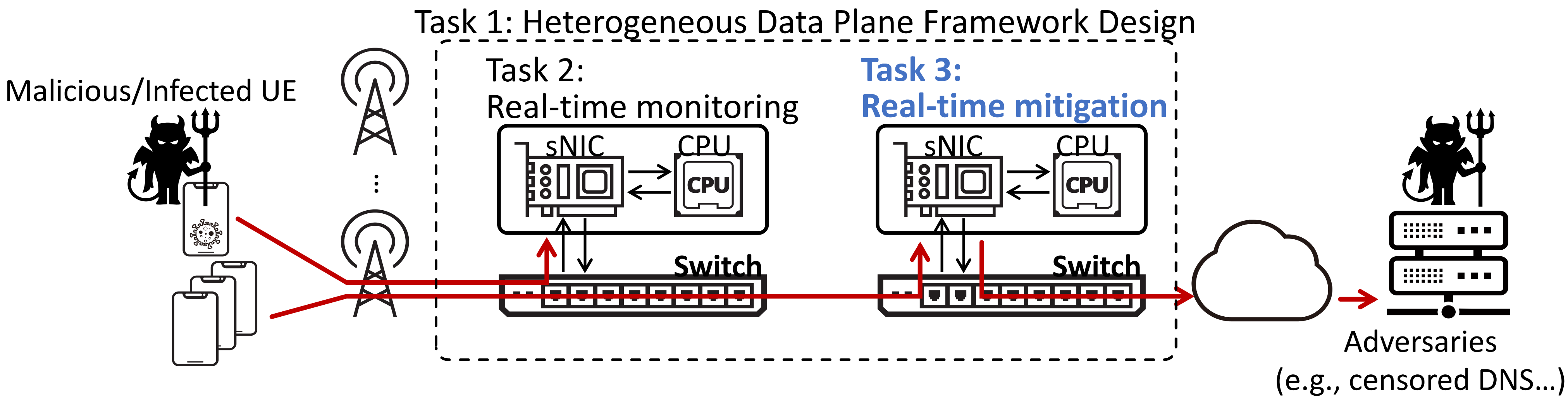


- Use heterogeneous data plane for real-time monitoring of 5G networks
  - 5G core based on multi-tier programmable data and control plane components
  - Line rate traffic monitoring for 5G resource management and anomaly detection

Task 2: Real-time Network Monitoring

- Goal: Leverage programmable dataplane at base stations and 5G core to enable real-time monitoring and security
- Applications:
  - **Resource management and mobility prediction** through analysis of control and data plane traffic in 5G core
  - **Protecting UEs** from both volumetric and slow attacks through UPF-based monitoring of control and data planes
  - **Securing 5G infrastructure** from rogue UEs and gNBs by aggregating monitoring data across devices

Task 3: Real-time Privacy Preservation/Attack Mitigation

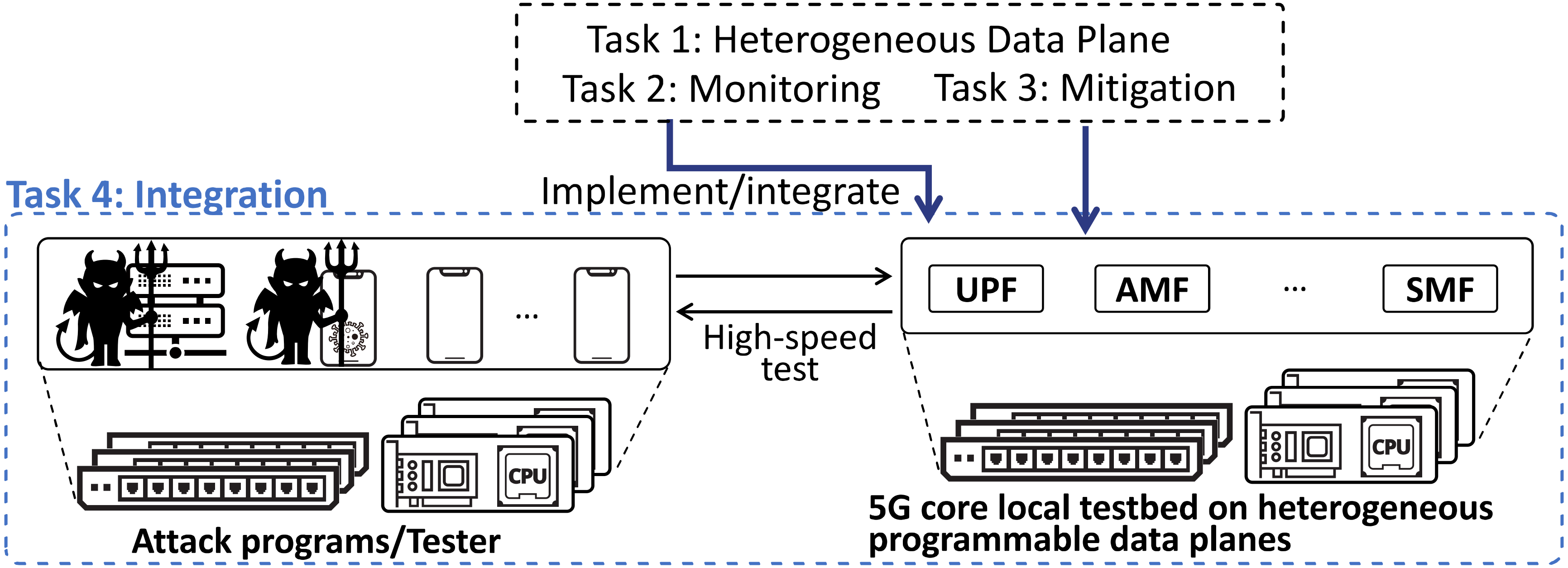


- Prevent attacks and preserve privacy for mobile users
  - Lightweight traffic encryption protocols to provide relationship anonymity
  - Traffic obfuscation techniques to prevent fingerprinting attacks

Task 3: Real-time Privacy Preservation/Attack Mitigation

- Goal: Privacy protection for users who access Web sites and various data
- Key techniques
  - **IP address obfuscation** through light weight anonymous routing protocol at the network layer and its implementation on a P4 switch
  - **Traffic morphing** to prevent fingerprinting attacks by inserting dummy packets and data
  - **DNS privacy protection** with a novel distributed and multiple-hop based approach of anonymization technique on DNS queries, and its design and implementation of its ‘lite-version’ on P4 switch

Task 4: Integration



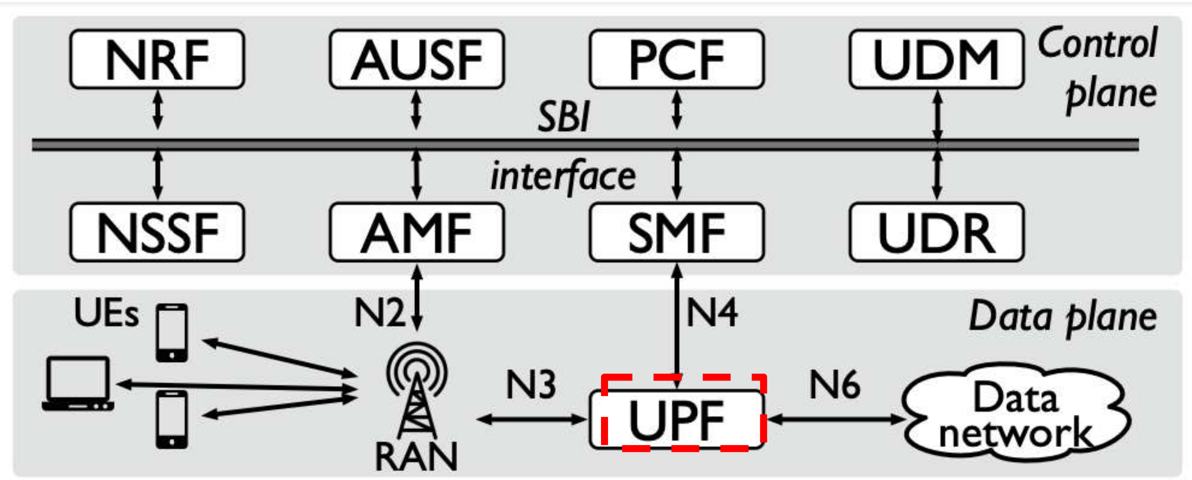
- Deploy a holistic system to study security and performance properties
  - Evaluate traffic monitoring and privacy preservation techniques on 5G testbed
  - Optimize the combination of hosts, P4 switches, and SmartNICs

Sample Projects

1. SmartNIC Accelerated Traffic Monitoring in the Cellular Core
2. Lightweight Anonymity Protocols for P4 Switches

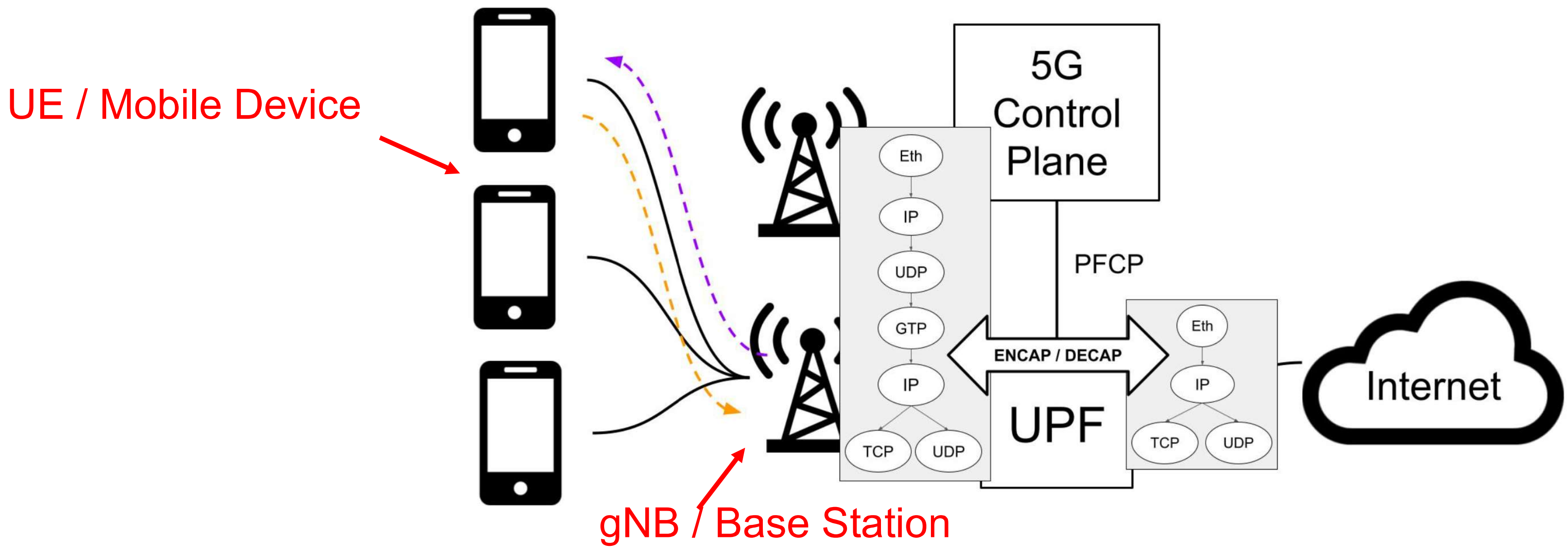
Synergy: Traffic Monitoring in the Cellular Core

- 5G Core (5GC) is the heart of a 5G mobile network
    - Establishes reliable, secure connectivity to network for end users
    - Mobility management, authentication/authorization, and policy management
- The 5GC is comprised of several control plane and dataplane NFs.
- The User Plane Function (UPF) is the primary dataplane component of the 5GC



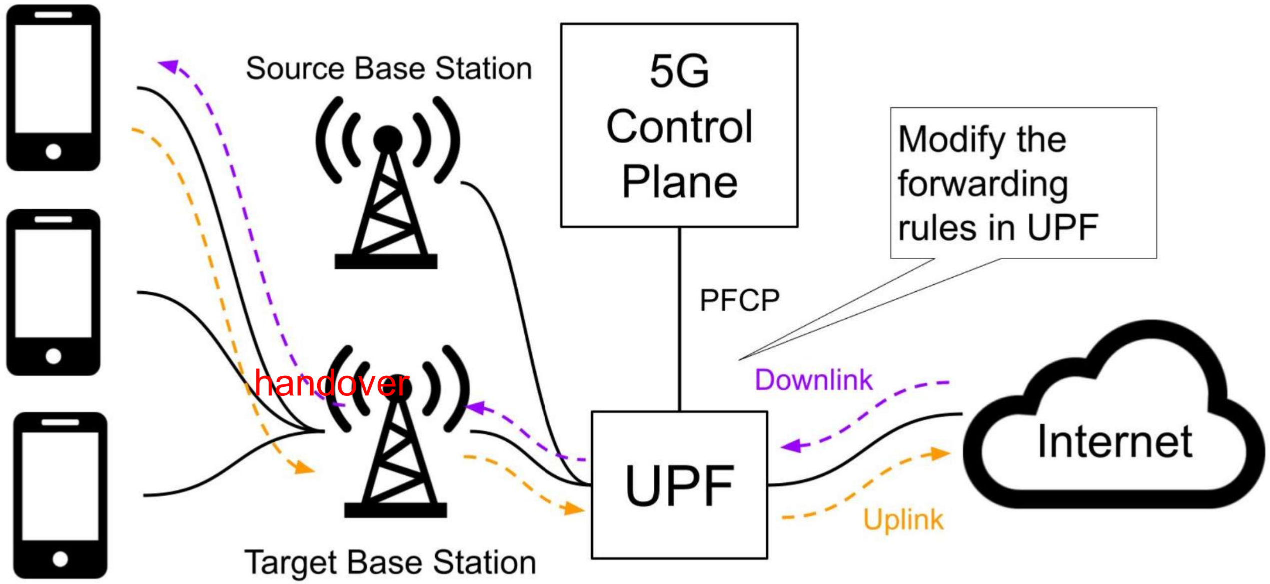
User Plane Function (UPF) : The 5G Dataplane

- Interconnect point between the mobile infrastructure and the data network.
- Implements complex rules for forwarding and tunneling.
  - Processes packets belonging to different sessions , priorities, including shaping and policing.
  - Must have high throughput and low latency→ spurious retransmissions and also packet loss.



UPF: Perform flow-state dependent processing

- Has to be aware of the idle and active transitions (Paging) → Save energy.
- Radio association change from one base station to another → Mobility.
- Lots of protocol msg exchanges that change the dataplane
  - Change must be affected quickly → Packets can be forwarded

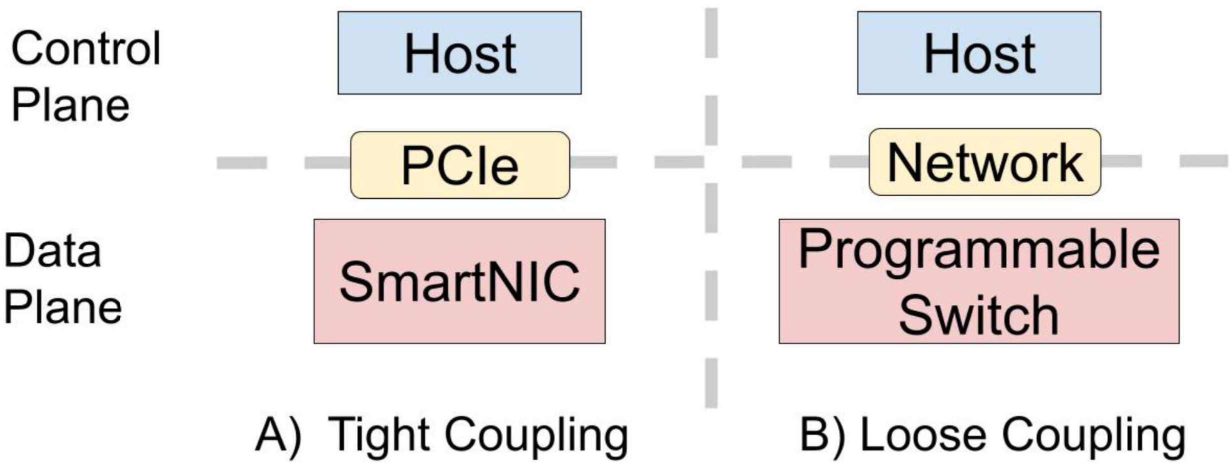


Improving Control/Data Plane throughput and latency

Require programmability: Rules have to be rapidly and frequently modified

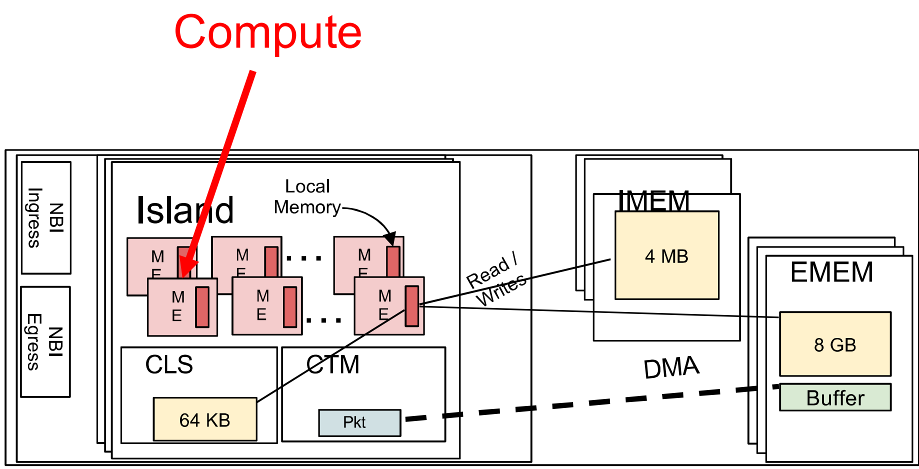
- Rules change when mobile device goes through handover, attach/detach, idle-active transition.
- Programmability of the SmartNIC can be tremendous advantage
- Take advantage of the tight coupling by using a SmartNIC accelerator.

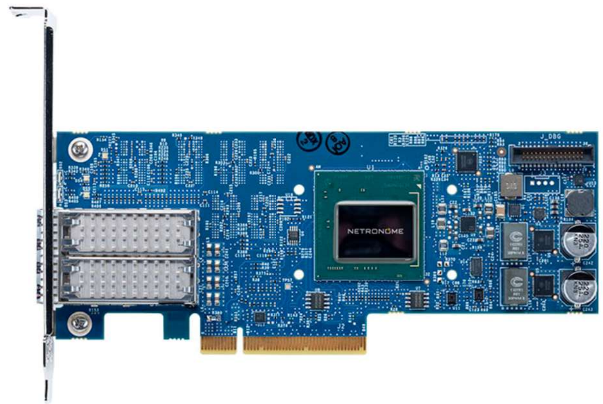
- **With a performant UPF, we can now enhance functionality: monitor the network; mobility prediction**
    - Prepopulate the state in 5GC to accelerate the control plane event → **Quicker handover.**
    - Enabler: Monitor control plane traffic in the SmartNIC → Predict Mobility → Prepopulate State



Synergy: P4 Programmable SmartNICs Primer

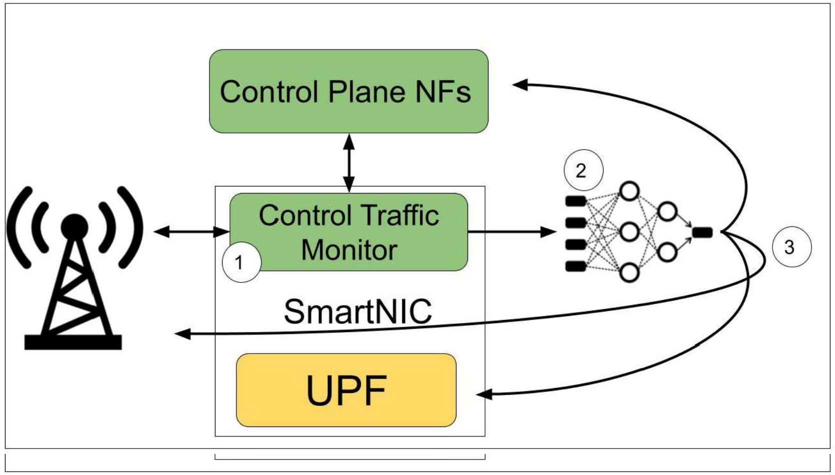
- We implemented Synergy on a Netronome Agilio LX 2x40GbE.
- 96 P4/ Micro-C programmable flow processing cores
  - Parallelism for packet forwarding processing.
- Memory Hierarchy (SRAM + DRAM)
  - Large memories (DRAM), slow to access → Buffering.
  - Smaller memories, bounded access latency → Forwarding.
- Dynamically push rules into the SmartNIC
  - Pushing rules in response to handovers / paging.
  - Takes advantage of the tight coupling with the host

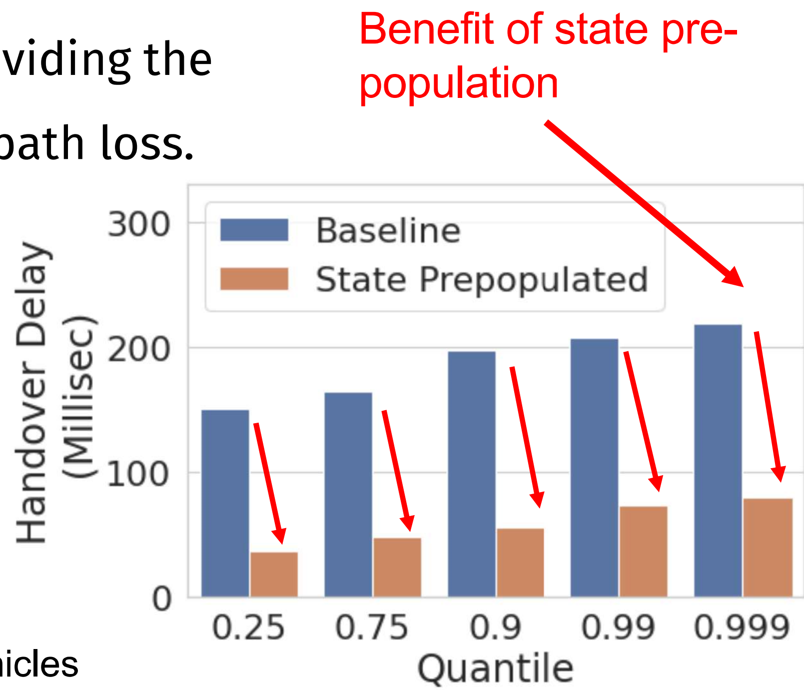




Application - Monitoring and Mobility prediction

- Carryout monitoring in the SmartNIC to do mobility predictions.
- Input: Mobile Device's Location report that the AMF requests; Output: UE's next base station.
- Model: Recurrent neural network model [1]
- **SUMO-based vehicular mobility dataset:**
  - 700k vehicle trips across 247 gNBs. [2]
  - At each point in time, the UE connects with the gNB providing the best communication conditions, measured in terms of path loss.

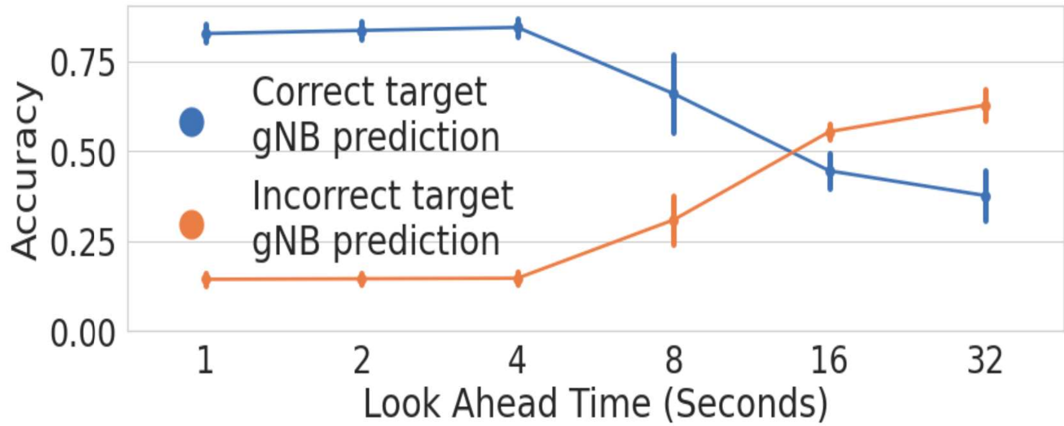


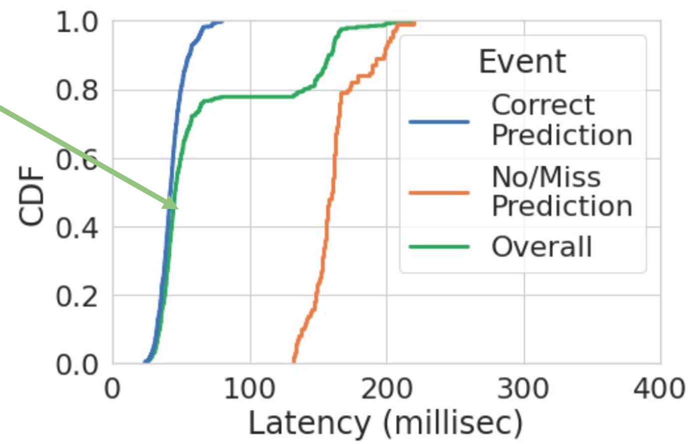


[1] Mobility aware and dynamic migration of MEC services for the internet of vehicles
[2] ttp://kolntrace.project.citi-lab.fr/

Benefit of Mobility Prediction and Tight coupling

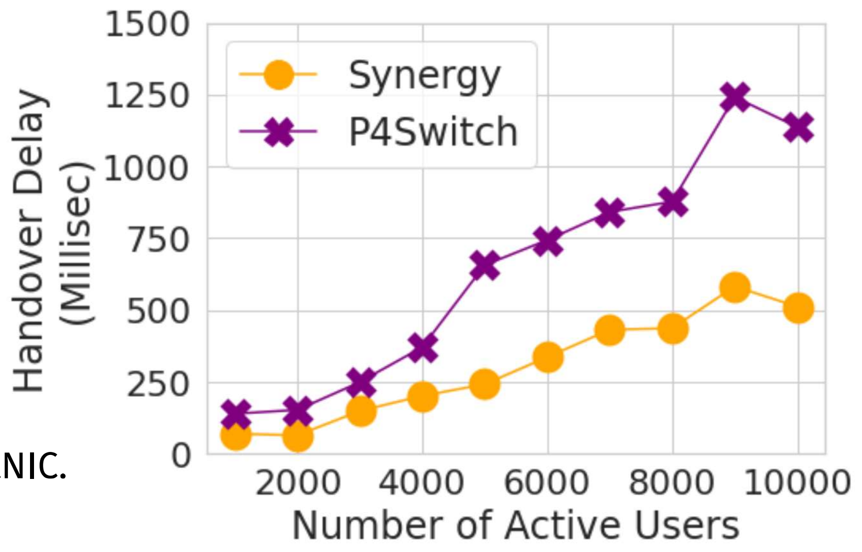
- Not possible to always have correct predictions
- Predict mobility with lookahead ~5 sec
  - Lookahead > 5 sec: Poor accuracy
  - Lookahead < 5 sec: Too many predictions
- Correct predictions reduce handover delays





Benefit of Mobility Prediction and Tight coupling

- Low programming latency → Lower Handover Delays
- Programmable Switches have been emulated here.
- Constraint with Programmable Switch: ~1200 rules/sec[1]



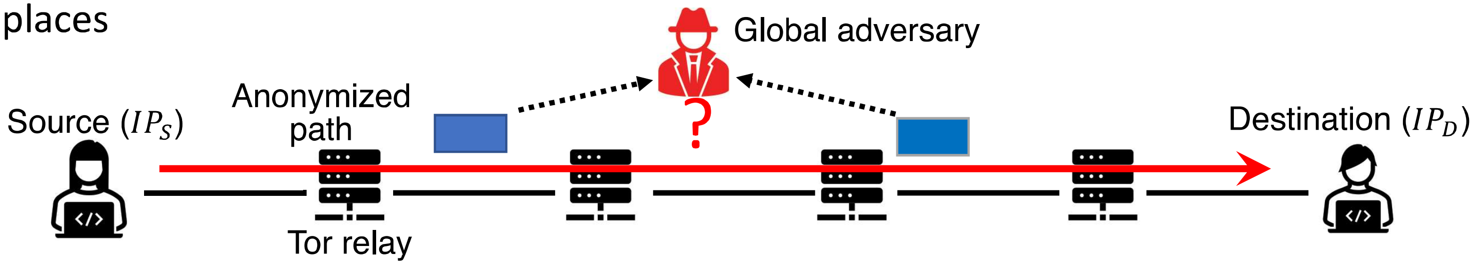
Summary

- Synergy accelerates the UPF throughput and reduces latency with the SmartNIC.
- SmartNIC-based UPF buffers packets:
  - Speed up control-to-data plane interaction
  - Reduces the impact on Handovers and Paging
- Handover latency reduced by monitoring and mobility prediction to prepopulate state.

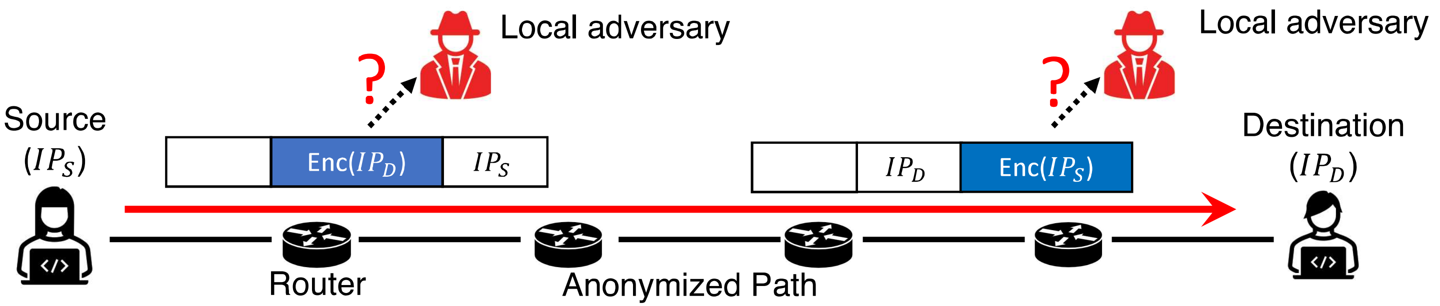
[1] NetWarden: Mitigating network covert channels while preserving performance (NDSS'20)

Background: Tor vs. Lightweight Anonymity Protocol in the Network Layer

- Tor assumes global adversary
  - Tor relays encrypt both headers and payloads to prevent a global adversary from correlating packets intercepted at multiple places



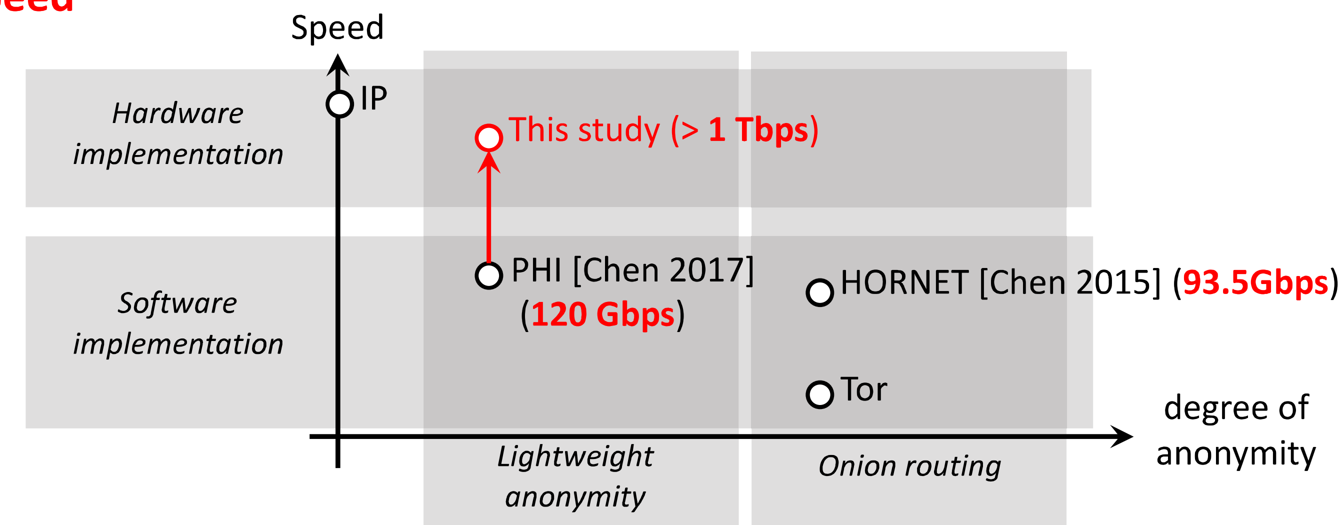
- Lightweight anonymity protocol assumes weak adversary
  - Routers obscure either source or destination address to prevent a local adversary from correlating source and destination addresses from packets intercepted at one place (relationship anonymity)
  - Advantages
    - High-speed forwarding owing to encryption of only headers
    - Short path length owing to the underlying IP routing path



[4] Yutaro Yoshinaka, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, "Design and analysis of lightweight anonymity protocol for host- and AS-level anonymity ," Computer Networks, Volume 222, 109559-109559, Feb. 2023.

Problems and Goals

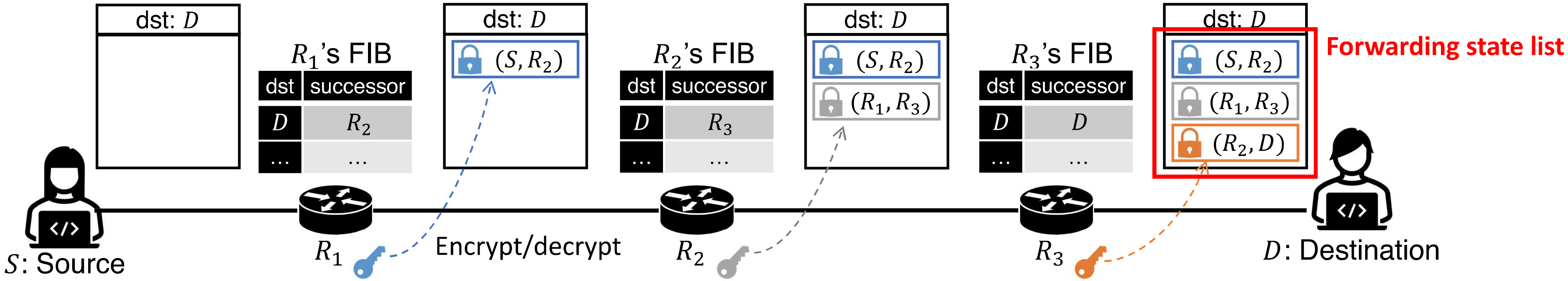
- Problems
  - Existing implementations only target **software switches**
    - Terabit speed, required for backbone routers, is unachievable on software switches
      - PHI [Chen 2017] achieves **120Gbps**
      - HORNET [Chen 2015], a protocol performing onion routing, achieves **93.5Gbps**
- Goals
  - Implementing lightweight anonymity protocols on **programmable switches** for anonymous communication at **terabit-class speed**



[Chen 2017] Chen, Chen, and Adrian Perrig. "PHI: Path-hidden lightweight anonymity protocol at network layer." *Proc. Priv. Enhancing Technol.* 2017.1 (2017): 100-117.
[Chen 2015] Chen, Chen, et al. "HORNET: High-speed onion routing at the network layer." Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security. 2015.

Lightweight Anonymity Protocol (AP)

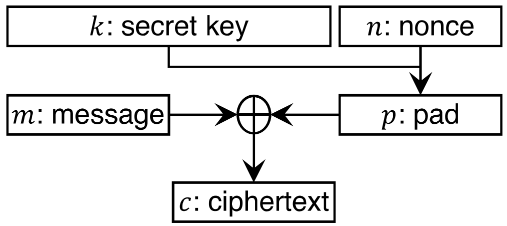
- Path setup phase
  - Routers create a forwarding state list in the onward trip to the destination
    - Pairs of predecessor and successor information (forwarding states) determined by IP routing
    - Encrypted with routers' secret keys and stored in packet headers
  - Destination replies with completed forwarding state list in the return trip



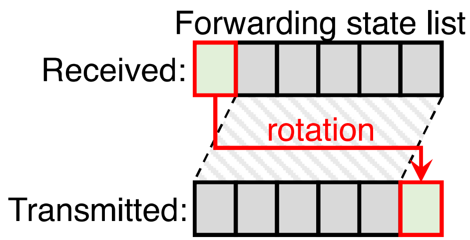
- Data transmission phase
  - Forwarding state list is recorded in packet headers
  - Routers retrieve and decrypt their own forwarding state for forwarding
  - Routers are stateless (states are kept in packet headers)

Design Challenges and Solutions

1. Cryptosystem
   - It must be able to be executed by a **limited instruction set** and a **limited number of stages**
   - Solution: **One-time pad cipher**
     - Suitable for encrypting on switches because encryption and decryption are equivalent
     - Half SipHash (keyed hash function) only uses addition, XOR, and bit rotation



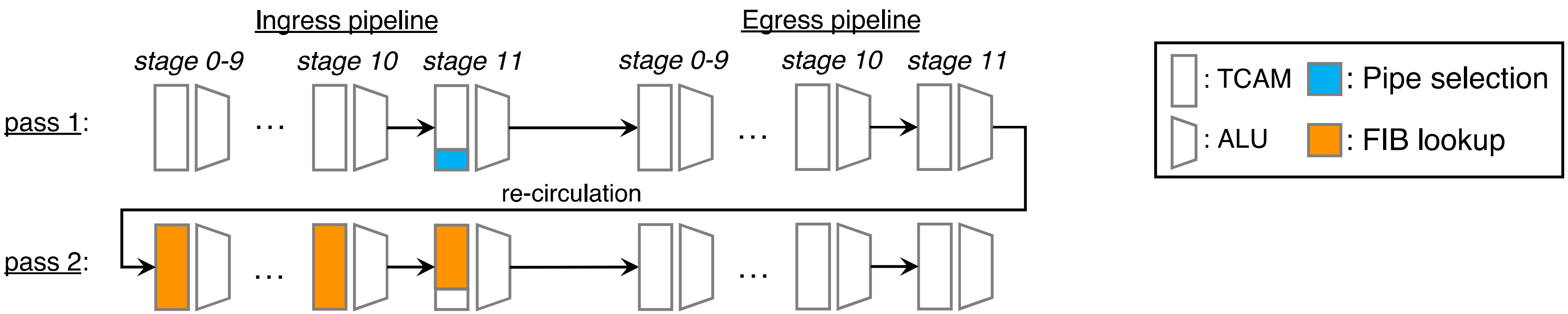
2. Data structure for accommodating a forwarding state list
   - It must satisfy anonymity requirements (e.g., **not leaking length of path**) and must be **lightweight to process** and not require extra computation
   - Solution: Rotatable array
     - The forwarding state list is **rotated after accessed**



3. IP routing support
   - It must handle **normal IP packets** as well for incremental deployment
   - It must keep **IPv4 full route** (500K entries)
4. Layout of the program on the switch's pipeline
   - Must implement the above functions with satisfying **Tofino's constraints**
   - Must minimize the number of recirculations for **terabit-class speed forwarding**

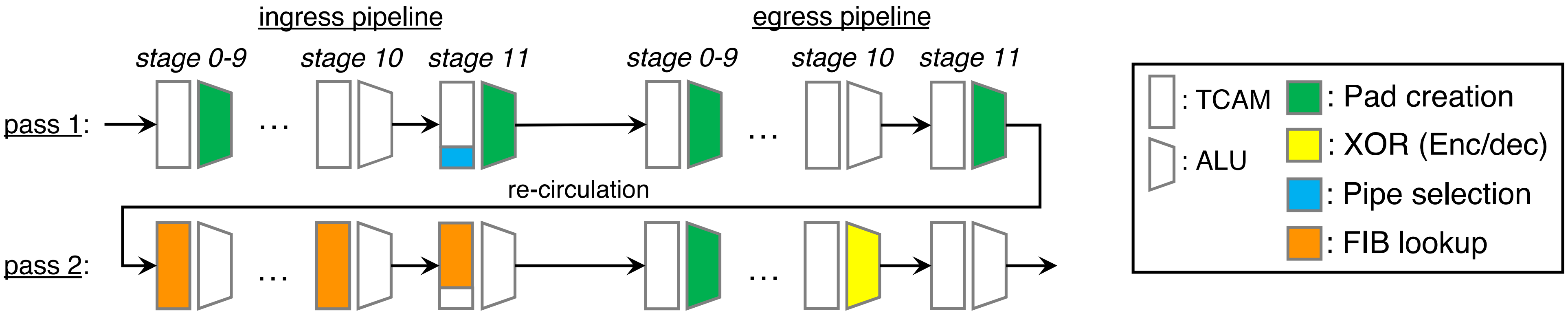
Layout of the Program on Switch Pipeline

- Layout constraints
  - A switch ASIC has 2 12-stage pipelines (ingress and egress pipeline)
  - Generating a one-time pad requires **32 stages**
  - Looking up FIB requires **12 stages**
  - Egress ports must be determined in the **ingress pipeline**
- Resulting Layout: We implement the functions with **one recirculation**
  - IP packet processing

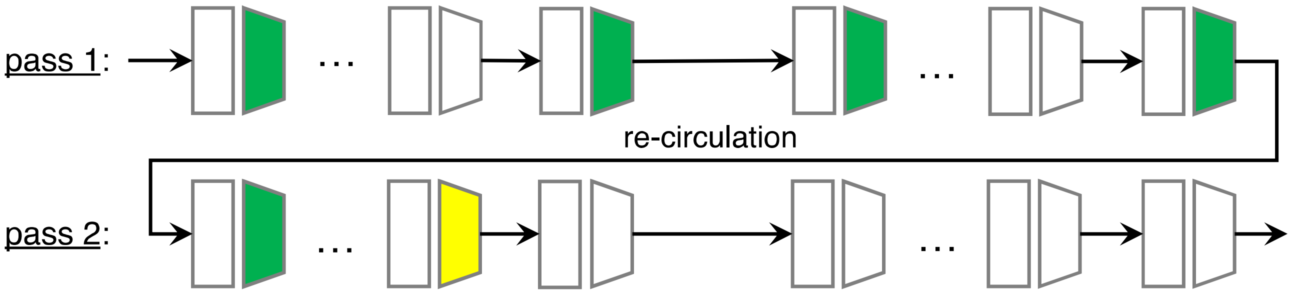


Layout of the Program on Switch Pipeline

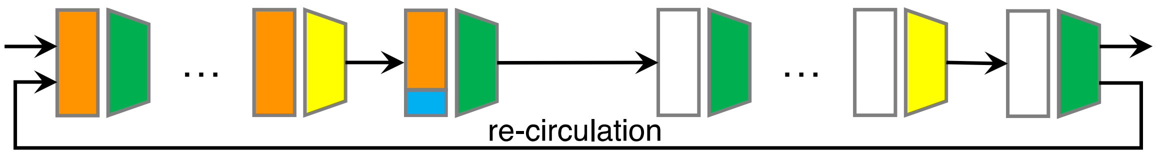
- Anonymity packet processing (path setup phase: encryption)



- Anonymity packet processing (data transmission phase: decryption

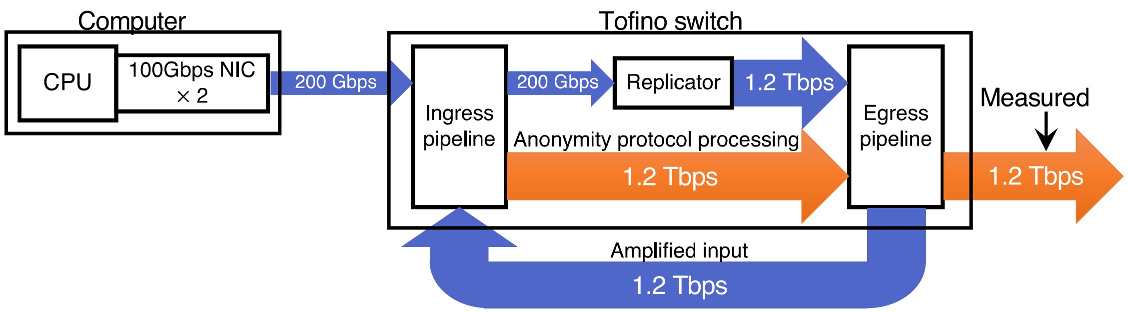


- Integrated pipeline layout

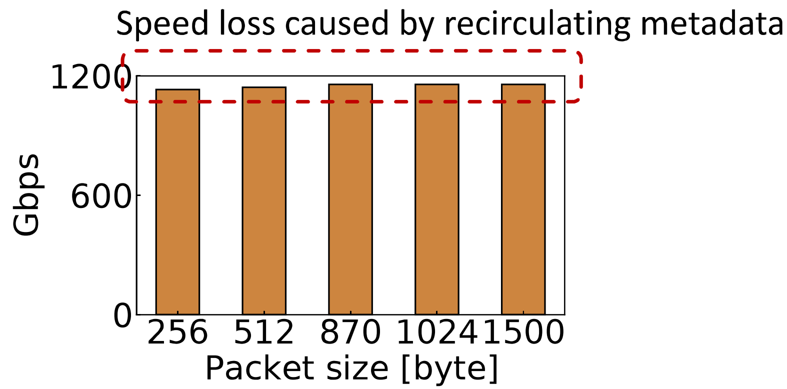


Evaluation and Future Directions

- Evaluation method
  - We implement designed pipeline using a Tofino switch (Wedge 100BF-32X **32 100 Gbps ports**)
  - Ideal forwarding speed is **1.2 Tbps**
    - 200 Gbps traffic is injected and amplified six times inside the switch
  - 2 ports are used for input, 12 are used for recirculation, and 12 are used for output
- Result: 1.16 Tbps forwarding speed



Experiment setup

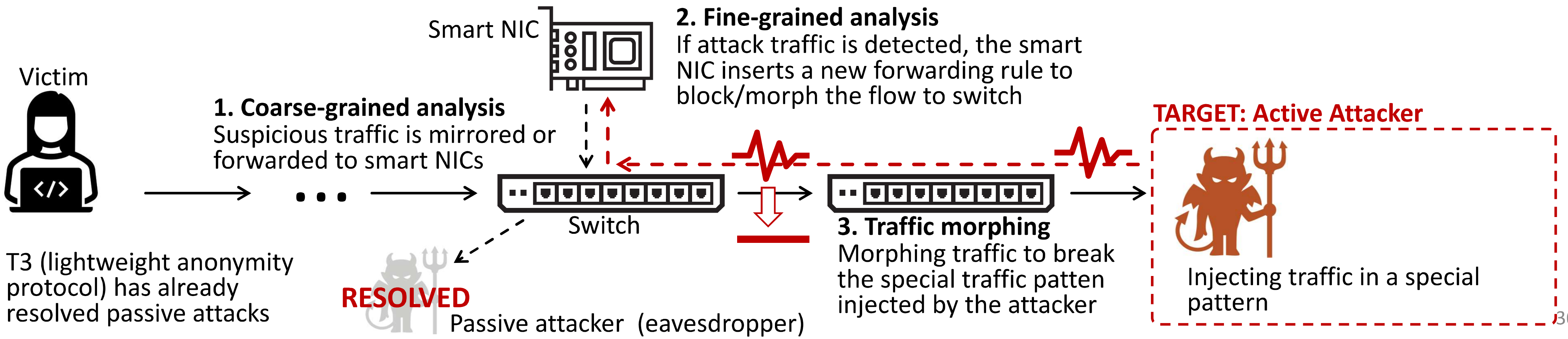


Forwarding speed result

- Ongoing research
  - Message authentication code (MAC) generation/verification **against attacks on path integrity**
  - **Stronger cryptosystem** like one-time pad with ShipHash instead of Half SipHash
- **Future research plan:**
  - **Smart NICs and switches for collaborative mitigation against active attacks**

Collaborative Smart NIC/Switch Secure and High-speed Anonymity Protocol

- Background: Anonymity protocols are **weak against active attacks**
  - Attackers can identify that a victim uses a certain router for anonymous communication
    - Injecting traffic in special patterns (like periodic bursts) toward the victim
    - Probing the perturbation caused by the injected traffic
- Approach: Smart NICs and switches collaboratively monitor and prevent the active attacks
  - Programmable switches
    - Coarse-grained analysis of active attacks
    - Traffic morphing to mitigate the attack
  - Smart NICs
    - High-speed and fine-grained monitoring of active attacks against anonymity protocol



Dissemination of Project Achievements: Summary

- We are designing the architecture to publish a joint paper
- Publications so far:
  1. Kentaro Kita, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, “Secure Middlebox Channel over TLS and its Resiliency against Middlebox Compromise,” in Proceedings of IEEE INFOCOM 2023, May 2023.
  2. Cuidi Wei, Ahan Kak, Nakjung Choi, and Timothy Wood, “Towards a Scalable 5G RAN Central Unit,” in Proceedings IEEE INFOCOM 2023 Workshop on Next-generation Open and Programmable Radio Access Networks (NG-OPERA), May 2023
  3. Ryu Watanabe, Ayumu Kubota, and Jun Kurihara, "Application of Generalized Deduplication Techniques in Edge Computing Environments," to Appear in Proceedings of AINA 2023 (M2EC-2023), Juiz de Fora, Brazil, Mar. 2023.
  4. Yutaro Yoshinaka, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, “Design and analysis of lightweight anonymity protocol for host- and AS-level anonymity ,” Computer Networks, Volume 222, 109559-109559, Feb. 2023.
  5. S. Panda, K. K. Ramakrishnan and L. N. Bhuyan, "Synergy: A SmartNIC Accelerated 5G Dataplane and Monitor for Mobility Prediction," *2022 IEEE 30th International Conference on Network Protocols (ICNP)*, Lexington, KY, USA, 2022.

Leveraging Heterogeneous Programmable Data Planes for Security and Privacy of Cellular Networks, 5G & Beyond

JUNO-3 PI Meeting

Aug. 28, 2025

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&

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George Washington University, Washington D. C.

Toru Hasegawa

Shimane Univeristy

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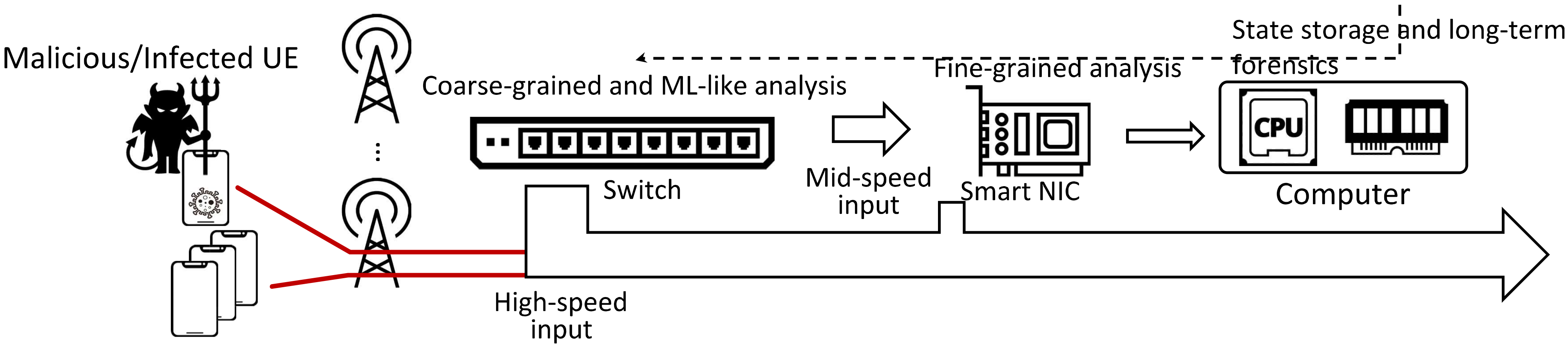
Osaka University

&

Toshiaki Tanaka and Jun Kurihara

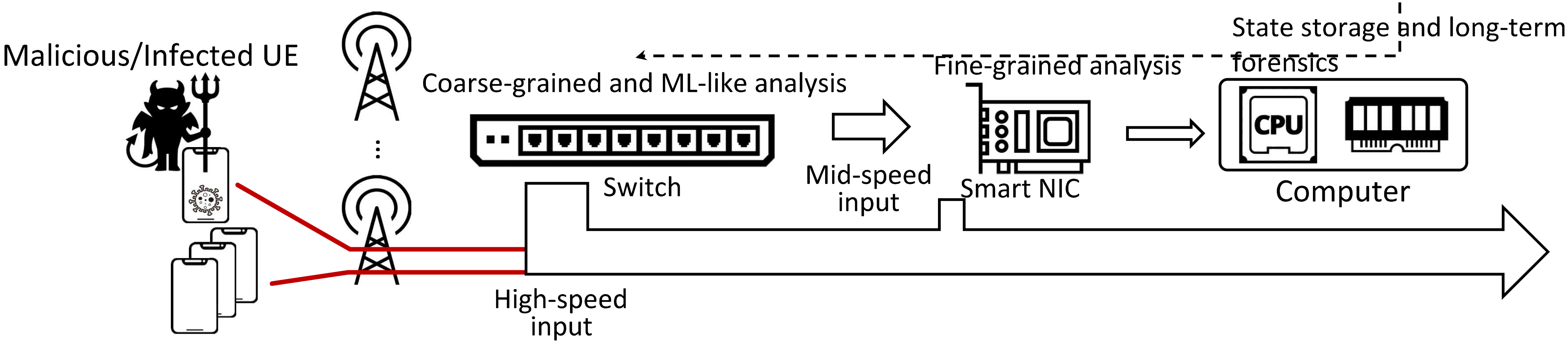
University of Hyogo

Programmable Data Planes for Network Performance Monitoring & Security



- Our project seeks to use high speed programmable switches, SmartNICs and end-host servers supporting network functions to provide security monitoring and privacy protection solutions
  - Develop an efficient, high performance network security solution, including for cellular networks
- Cellular networks support a growing amount of traffic from mobile and Internet of Things (IoT) devices
  - Implementations moving to software-based environments: potential for increased vulnerability to security attacks, including violation of user privacy through eavesdropping
  - More low-volume, slow and stealthy attacks: difficult to detect, need more memory and compute capacity
- Monitoring: we will develop a collaborative filtering system for real-time monitoring of network traffic
  - Most of the traffic processed by high-speed programmable switches to extract coarse-grained metrics
  - Suspicious traffic redirected to programmable SmartNICs or the host for detailed forensics

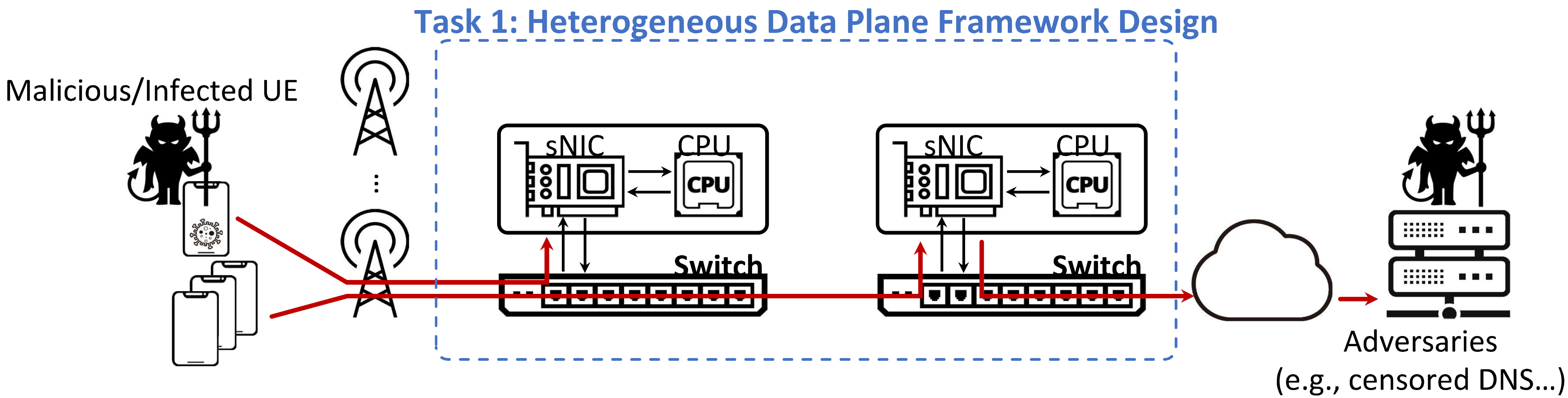
Programmable Data Planes for Network Performance Monitoring & Security



- Privacy Protection: utilize P4 programmable switches for anonymization and privacy protection
  - Lightweight Anonymization at Terabit rates within the network layer with high-speed P4 switches
  - Use traffic morphing to handle fingerprinting attacks
- Project builds on decade-long work on switching, SmartNIC and NFV work by PIs and collaboration between the PIs based in the US and Japan
- Societal Impact: Provide strong threat prevention and privacy preservation of cellular network users

Overview of Project Accomplishments

Tasks 1-2: Heterogeneous Data Plane Monitoring

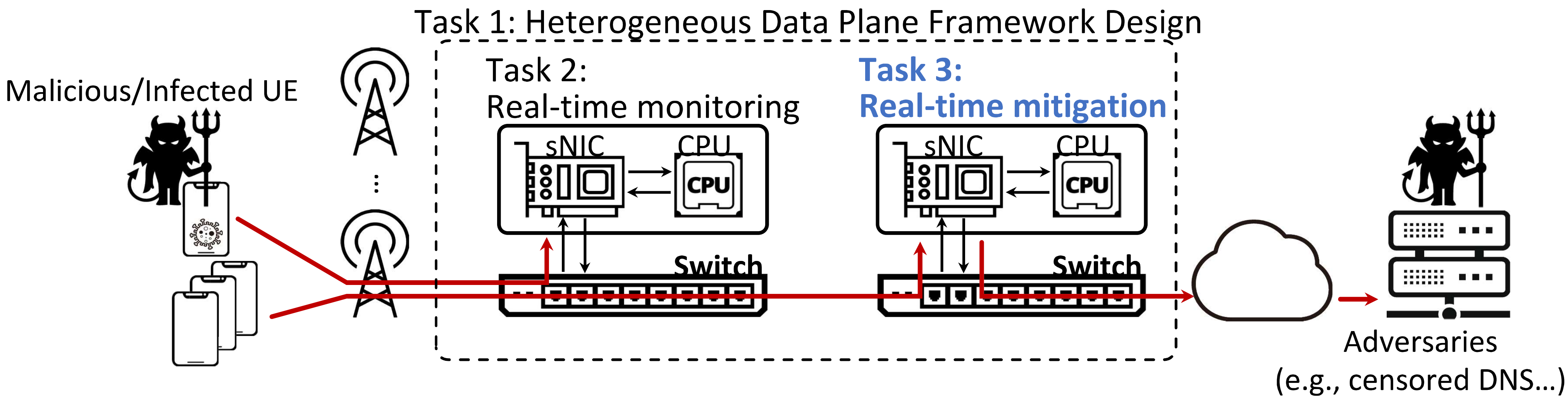


- Design a programmable data plane framework to leverage heterogeneity:
  - P4 Switches: High bandwidth (Tbps), limited memory (MBs)/programmability
  - SmartNICs: Moderate bandwidth (Gbps), moderate memory (GBs); Programmable
  - Host CPUs: Limited bandwidth, large memory (TBs), general purpose CPUs
- Use heterogeneous data plane for real-time monitoring of cellular network
  - 5G core based on multi-tier programmable data and control plane components

Task 1-2: Heterogeneous Data Plane Monitoring

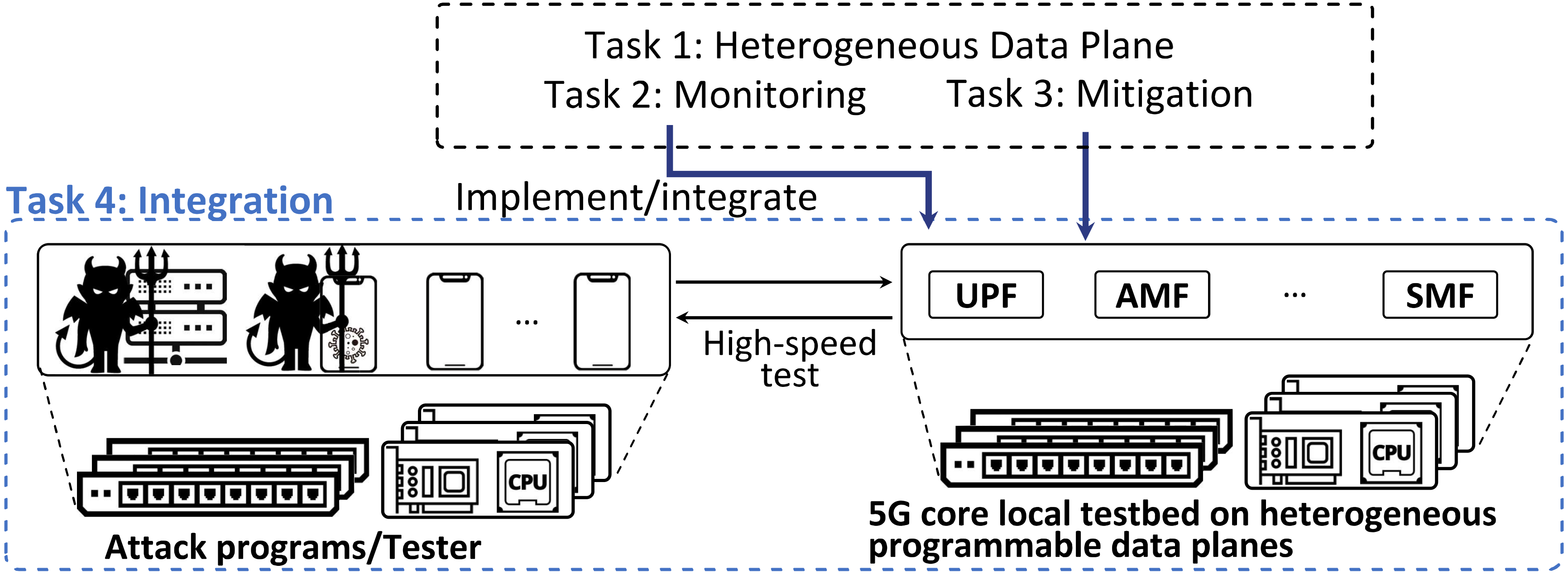
- Goal:
  - Coordinate protocols between various programmable network devices to overcome their limitations while optimizing their strengths, to enable real-time monitoring and security
- Key techniques
  - **Cooperative flow filtering** and state caching across heterogeneous programmable network devices
  - **In-network ML inference:** get high throughput by using the pipelined processing of packets on P4 switches and SmartNICs and slicing of GPUs on hosts
  - **Optimization algorithms** that use models of component capabilities to effectively determine which traffic monitoring modules to place on which types of data plane hardware

Task 3: Real-time Privacy Preservation/Attack Mitigation



- Prevent attacks and preserve privacy for mobile users
  - Lightweight traffic encryption protocols to provide relationship anonymity
  - Traffic obfuscation techniques to prevent fingerprinting attacks

Task 4: Integration



- Deploy a holistic system to study security and performance properties
  - Optimize the combination of hosts, P4 switches, and SmartNICs
  - Evaluate traffic monitoring and privacy preservation techniques on 5G testbed

Task 1/2: Heterogeneous Data Plane for Real-Time Monitoring

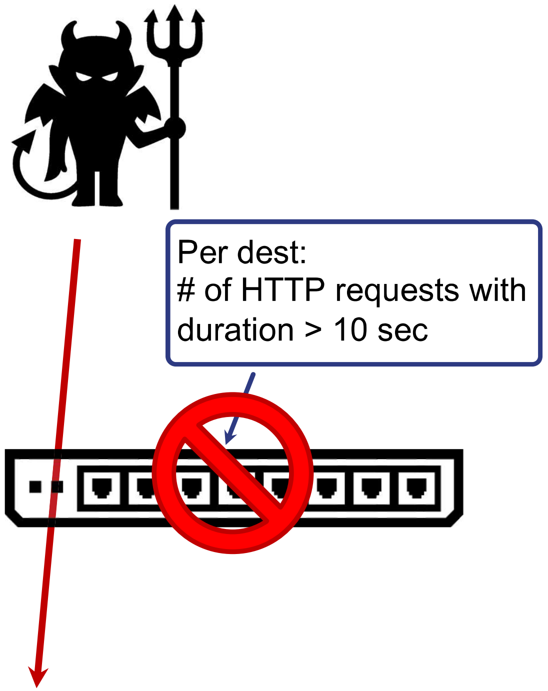
Low Volume and Slow Attacks

- **SYN Flood Attacks**
  - Sends only a few packets to exhaust a target's kernel socket resources by exploiting the TCP 3-way handshake.
- **Port Scan Attacks**
  - Common method for discovering exploitable open ports of servers on the network.
- **SSH Brute-forcing**
  - An attack where one or more nodes use different username/password combinations to try to log in to a site.
- **Slowloris**
  - Holds open a connection by continuously send partial HTTP GET requests with incomplete headers at a slow rate to keep sockets from closing
- **Slowbody/RUDY**
  - Holds open a connection by continuously sending incomplete HTTP POST requests with large Content-Length value within the HTTP header at a slow rate to keep sockets from closing

Hard to detect and can be extremely damaging to end hosts!

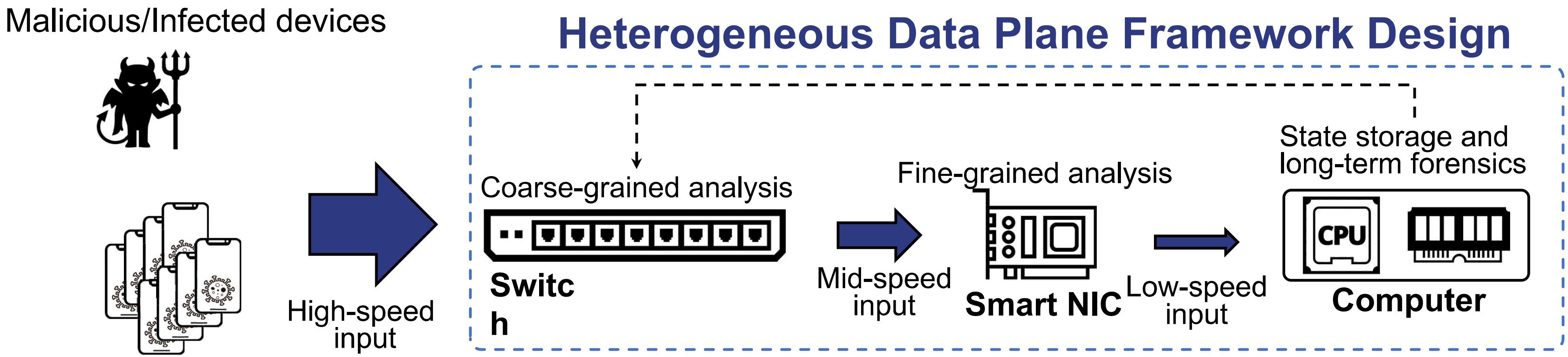
Programmable Switch Constraint Implications

- Slowloris Attack [1]
  - keeps open a very large number of connections to a target web server
  - difficult to serve legitimate web requests
- A constrained programmable switch could conduct coarse-grained analysis [2]
- A host-based IDS can then conduct fine grained analysis [3]
  - SmartNICs/FPGA have been widely used for monitoring [4, 5]
  - SmartNICs
    - Have fewer hardware limits compared to switches
    - Can reduce costly bus and host overheads
    - have acceleration functionality - encryption, hash calculation



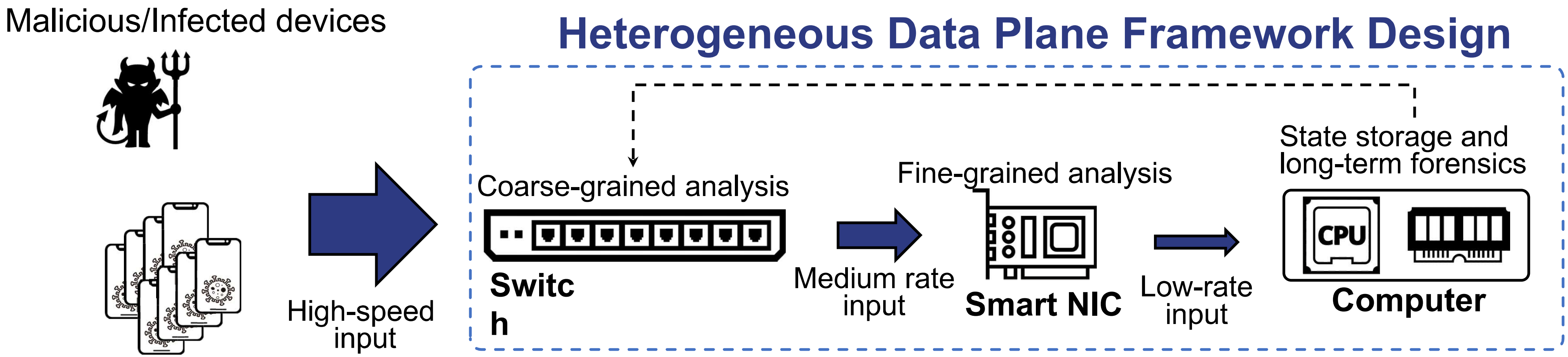
[1] Slowloris DDoS attack (CloudFlare)
[2] Sonata: Query-driven Streaming Network Telemetry (SIGCOMM 2018)
[3] Zeek https://zeek.org
[4] Achieving 100Gbps Intrusion Prevention on a Single Server (OSDI 2020)
[5] Turboflow: information rich flow record generation on commodity switches (EuroSys 2018)

Heterogeneous Data Plane Monitoring



- Objective: Finding “a needle in a haystack”
  - Monitor low-volume and slow attacks in a high-speed network
- Approach:
  - Cooperative flow filtering and state caching across heterogeneous programmable network devices
  - Coordination among heterogeneous devices to overcome their limitations while optimizing their strengths, to enable real-time security monitoring

The Dataplane's Strengths and Weaknesses



	Throughput	Memory	Programmability
Switch (per pipe)	1.6 Tbps ⇈	10 MB ⇊⇊	P4
SmartNIC (per port)	40 Gbps	4 GB	P4 + MicroC
Host (per core)	10 Gbps	25 GB	General purpose

Harnessing Heterogeneous Data Plane Devices

1. How to perform **stateful** monitoring of Terabit scale traffic to detect **low and slow attacks**?
   - **Differentiate between suspicious and benign flows as quickly as possible**
2. How to overcome the **limited memory** of the switch and the **limited bandwidth** of the NIC/host?
   - **“Flip-the-script”: Use specialized switch data structures to track benign flows and use NIC/host to analyze & identify suspicious traffic**
   - **Rather than Sketch-like approaches that focus on finding ‘elephant malicious flows’**
3. How to coordinate multiple devices to work together?
   - **Optimize communication via data plane paths to be substantially quicker than control plane updates**

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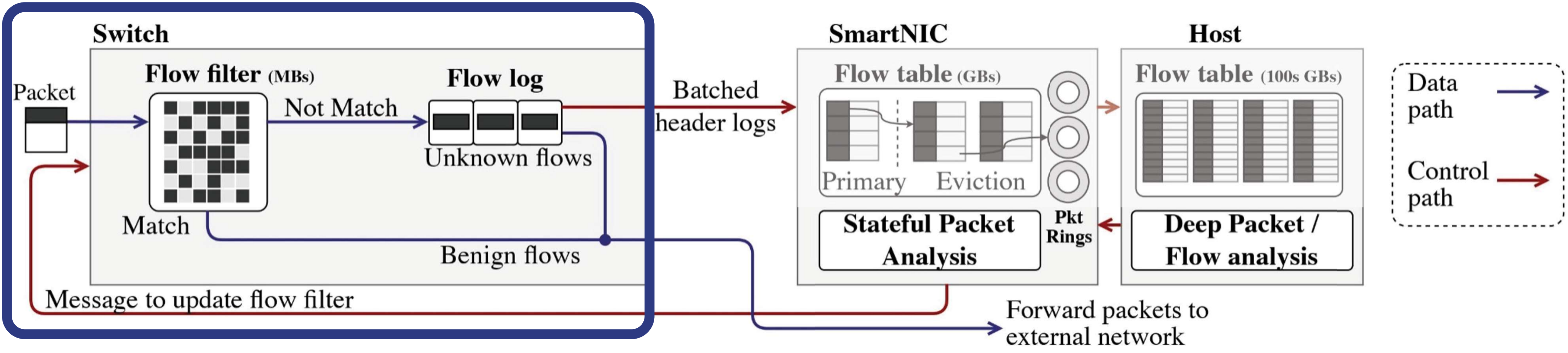
Benign vs. Suspicious Flows

	Benign Flows	Suspicious Flows	Examples
TCP connection establishment	3 packets	1 or 2 packets	Syn Flood, Port Scan
Connection Authentication	often > 20 authentication-related packets within a short time	often < 10 authentication packets within a short time	SSH Brute Forcing, FTP Brute Forcing
HTTP Requests	Full HTTP Requests	Partial Requests	Slowloris, Slowbody/RUDY

Often it is possible to detect "good" flows quickly

Packet Processing Flow



- **SmartNIC/Host Analysis**:
  - Treat first few packets of all flows as "**suspicious**" and send for monitoring
  - Mark flows as "**benign**" if classified safe
- **Switch**
  - ✗ Stateful processing
  - ✓ Filter that reduces the load on and communication to the host.

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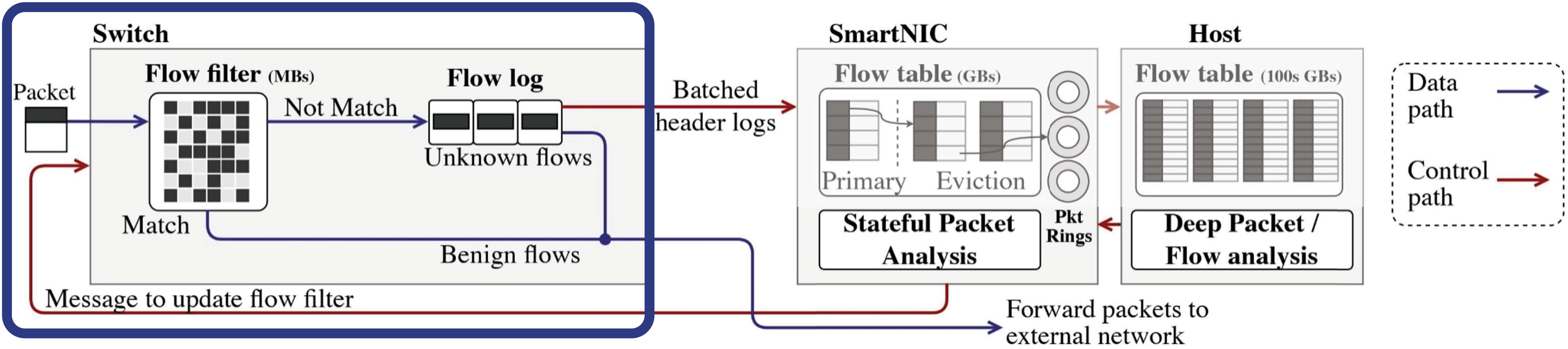
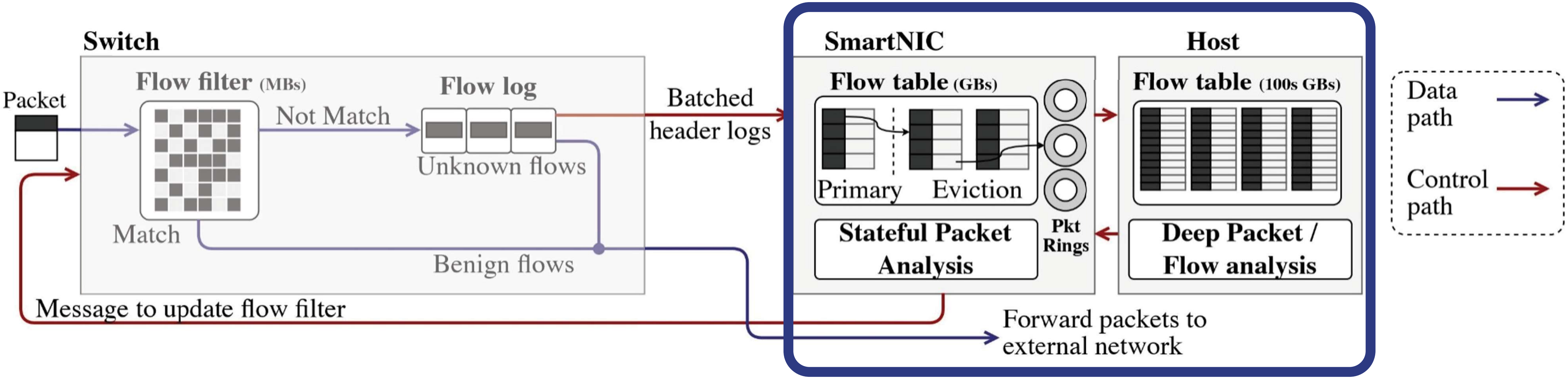
Switch Data Structures



- Tracks **benign flows** to be forwarded directly to network in a space-efficient manner with simple operations
  - Switch flow filter is based on Bloom and Cuckoo filters
- Extended to balance risk (false positives) and overhead (false negatives)
  - False positives caused by the nature of the Bloom filter
    - Identify suspicious flows as benign
  - False negatives because of deletion of old flows
    - Identifies benign flows as suspicious

NIC/Host Data Structures



- **SmartNIC/Host Flow Tables [6]**
  - Consists of hash tables and ring buffers
  - Supports 25M to 100M flow entries on the smartNIC
  - Lossless tracking both packet-level and flow-level features at 43 MPPS
  - Host retains information about all flows seen so far

[6] Sourav Panda, Yixiao Feng, Sameer G Kulkarni, K. K. Ramakrishnan, Nick Duffield, and Laxmi N. Bhuyan, "SmartWatch: Accurate Traffic Analysis and Flow-state Tracking for Intrusion Prevention using SmartNICs," CoNEXT, Dec. 2021.

Harnessing Heterogeneous Data Plane Devices

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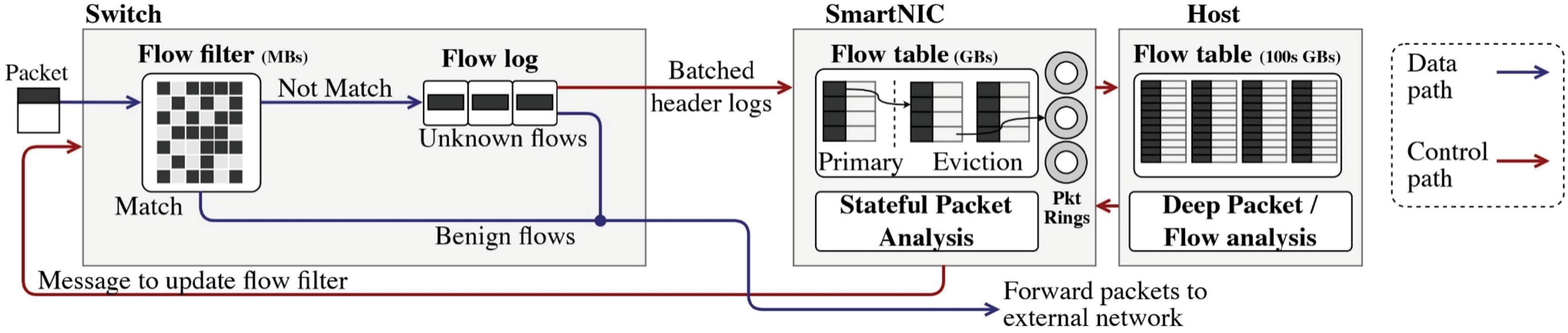
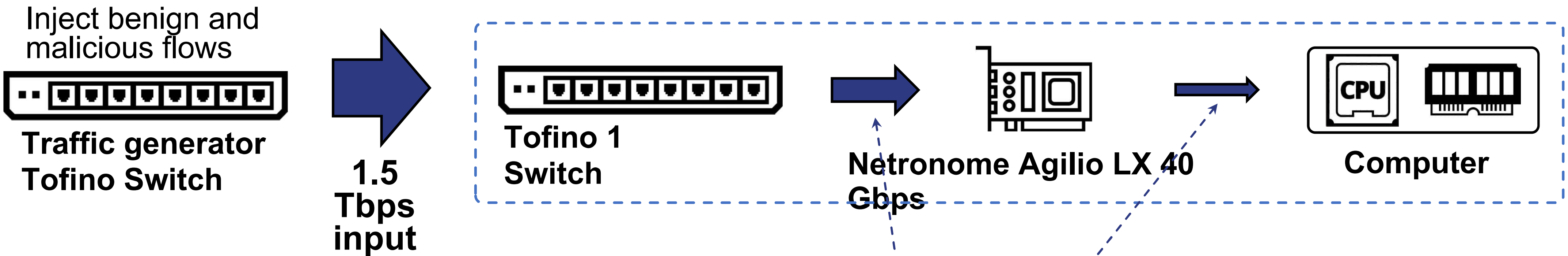
Data Plane Communication

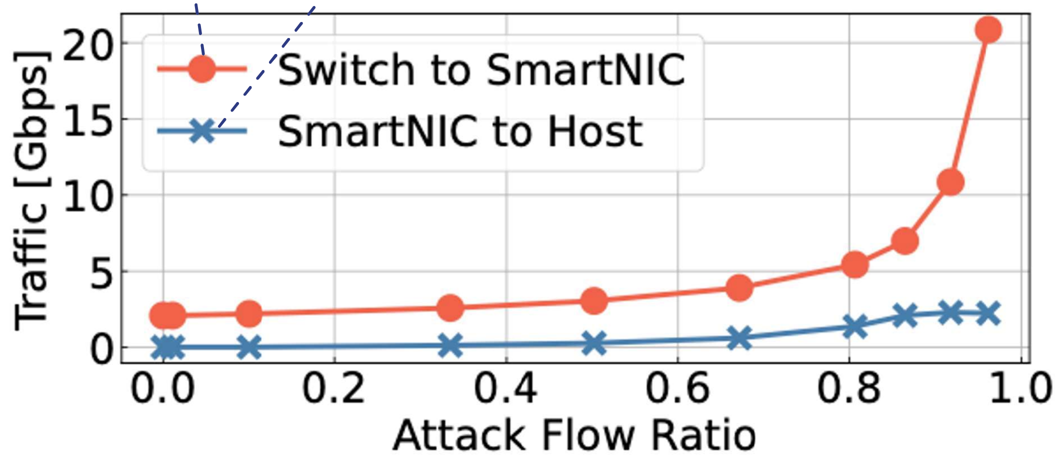


- **Fast communication among the dataplane devices**
  - **Data Plane Messaging:**
    - Avoid slow control plane protocols to update the switch flow filter
- **Efficient communication between the dataplane devices**
  - **Packet Truncation:**
    - Only send key flow information from the packet header
  - **Packet Batching:**
    - Buffers flow information from several packets in a flow log, then transmits them to the SmartNIC/Host when the flow log is full

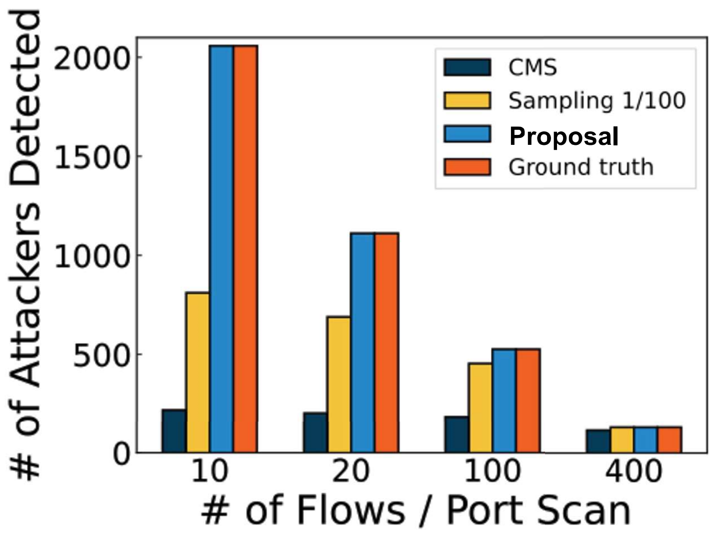
Evaluation: Traffic Load on SmartNIC/Host

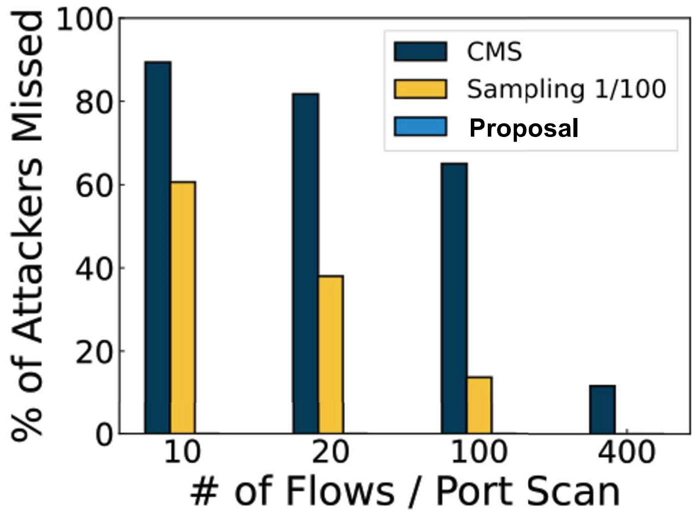


- **1.5 Tbps of traffic incoming to switch**
- Even for large numbers of attack flows, the volume to the SmartNIC remains low, only passing 10 Gbps for α > 0.9.
- 99.3% reduction in traffic that reaches host, could be easily handled by a single core



Evaluation: Detection Performance





- CountMin Sketch can generally detect the heaviest attack flows in high accuracy but does poorly on detecting low-rate attack flows.
- Sampling 1/100 is also good at detecting heavier attack flows but misses a certain portion of low-rate attacks.
- Proposal can detect low-rate attacks quite in high accuracy and also can handle heavy attacks.

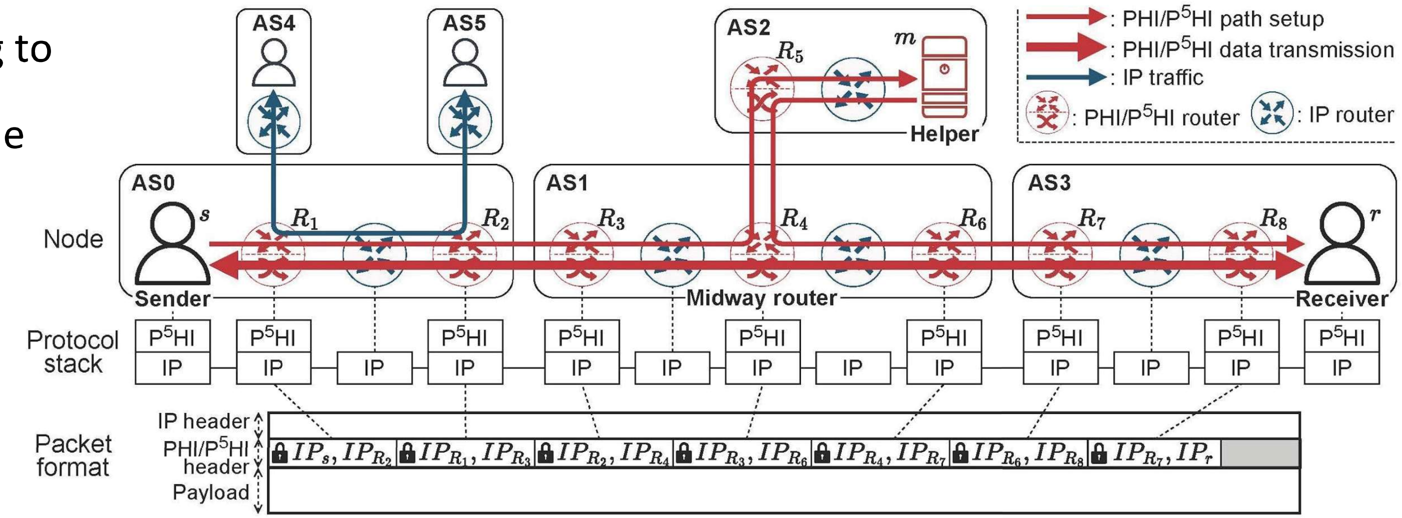
Task 3/4: Real-time Privacy Preservation and Integration

Achievements of Task 3 and 4

- **IP address obfuscation**
  - Implements Lightweight Anonymity Protocol (AP) on a Tofino-based programmable switch
  - Demonstrates high-speed lightweight AP communication between the U.S. and Japan over an intercontinental testbed
- **DNS privacy protection**
  - Designs and implements a multiple-relay-allowed anonymization scheme, µODNS (Mutualized Oblivious DNS), whereas existing schemes use a single relay

Lightweight Anonymity Protocol (AP)

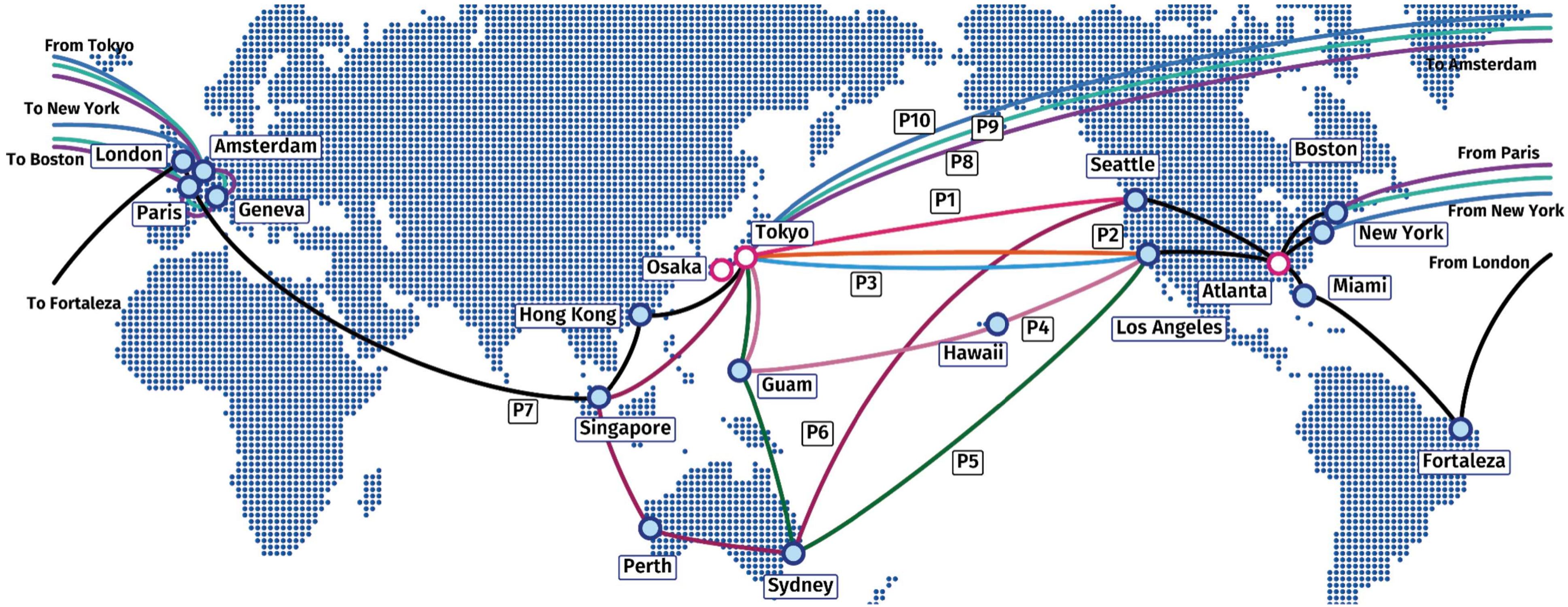
- PHI (Path-hidden lightweight anonymity protocol)
  - Assumption: Local adversary
    - Weak but reasonable adversary who captures packets at a single point of the path
  - Relationship anonymity
    - Routers obscure either source or destination address to prevent a local adversary from correlating source and destination addresses
  - Advantages
    - High-speed forwarding owing to encryption of only headers
    - Short path length owing to the underlying IP routing path
- **P5HI (P4 PHI)**
  - **Hardware-based AP implementation**
  - For both Tofino 1 and 2 switch



Yutaro Yoshinaka, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, “Design and analysis of lightweight anonymity protocol for host- and AS-level anonymity ,” Computer Networks, Volume 222, 109559-109559, Feb. 2023.

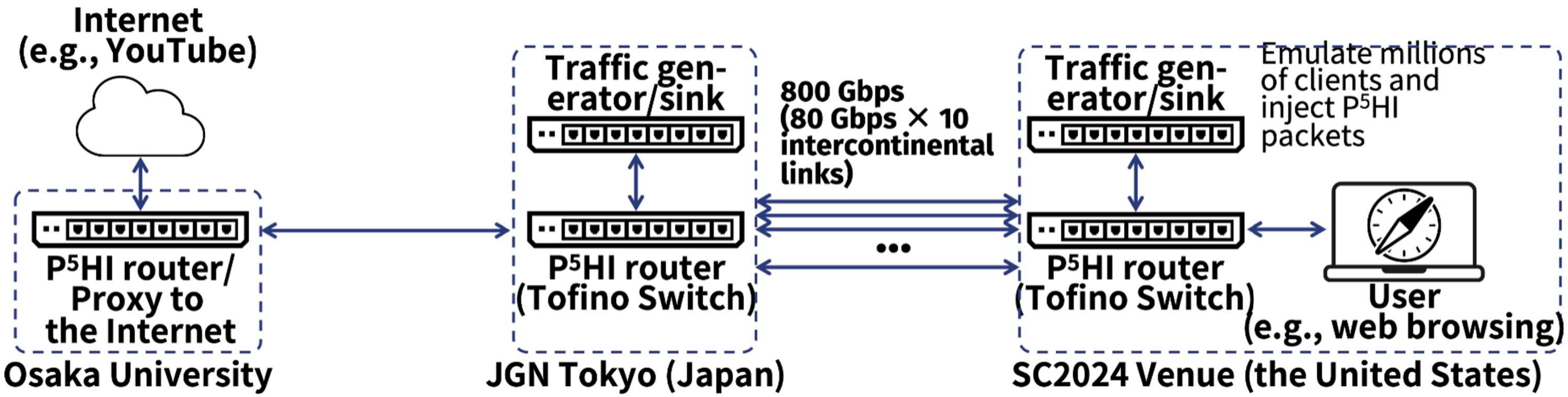
P5HI Experiments over an Intercontinental Testbed

A dedicated **800 Gbps connection** (10 x 80-Gbps links) was established between Tokyo (the NICT's testbed node) and Atlanta (SC24 venue)
(It made possible through the extensive support of the NICT testbed team, the KDDI network operations team, and 21 collaborating institutes)



Demonstrations of P5HI at SC24

1. Demonstration of high-speed anonymous communication
    - **588.4 Gbps anonymous communication between Japan and the U.S.**
        - Performance limited by packet filtering on two links and rate control on one link
2. Demonstration of real applications over anonymous communication
    - **4K YouTube video streaming** from the Internet traversing a proxy server at Osaka University, passing through the JGN Tokyo node, and reaching the SC venue

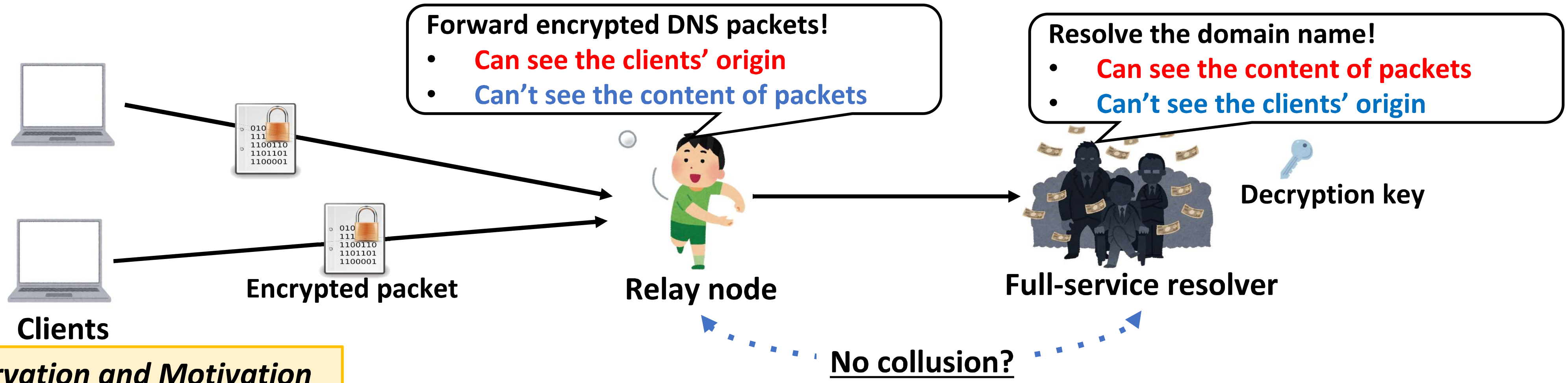


DNS Anonymization against Colluded Network Nodes

Background

Recent increase and exposure of Internet censorship
➜ Strong demands of DNS privacy against **DNS resolvers**
➜ Novel **DNS-dedicated anonymization schemes** have been proposed (e.g., Oblivious DNS over HTTPS (ODoH, RFC9230), a.k.a. Apple Private Relay)

Such schemes are based on the single-relay approach to hide the clients' origin from the censoring resolver



Observation and Motivation

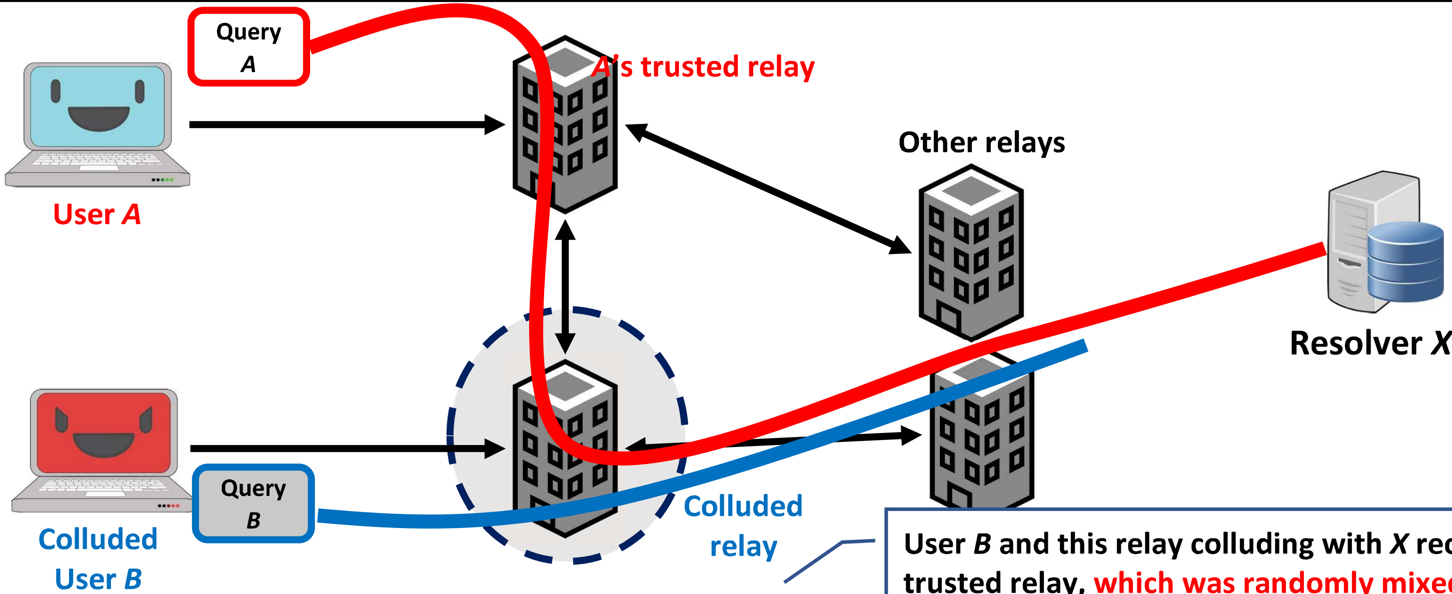
The DNS-dedicated single-relay approach *works fast and maintains UX*, but is easily corrupted when the relay colludes with the target resolver. (In fact, relay nodes and resolvers typically run by just few big techs.)
➜ Our aims are to **design a novel collusion-resistant DNS anonymization scheme**, and to **prove the scheme still maintains UX** in terms of its response speed.

Approach: The Mix-Net

To those ends, we have proposed **multiple-relay-allowed anonymization scheme, μODNS (Mutualized Oblivious DNS), taking an approach of *Mix-Net*** :

- Each relay node ***mixes*** incoming query packets to hide their origins, where origins = **not only clients *but also other relays***
- **Each Client randomly chose the path and # of relays (> 0)**, but the first hop is supposed to be always trusted for the client.

➜ Attacker nodes cannot deterministically distinguish origins of query packets since **observed queries are mixed ones that traveled through random path of random length**.



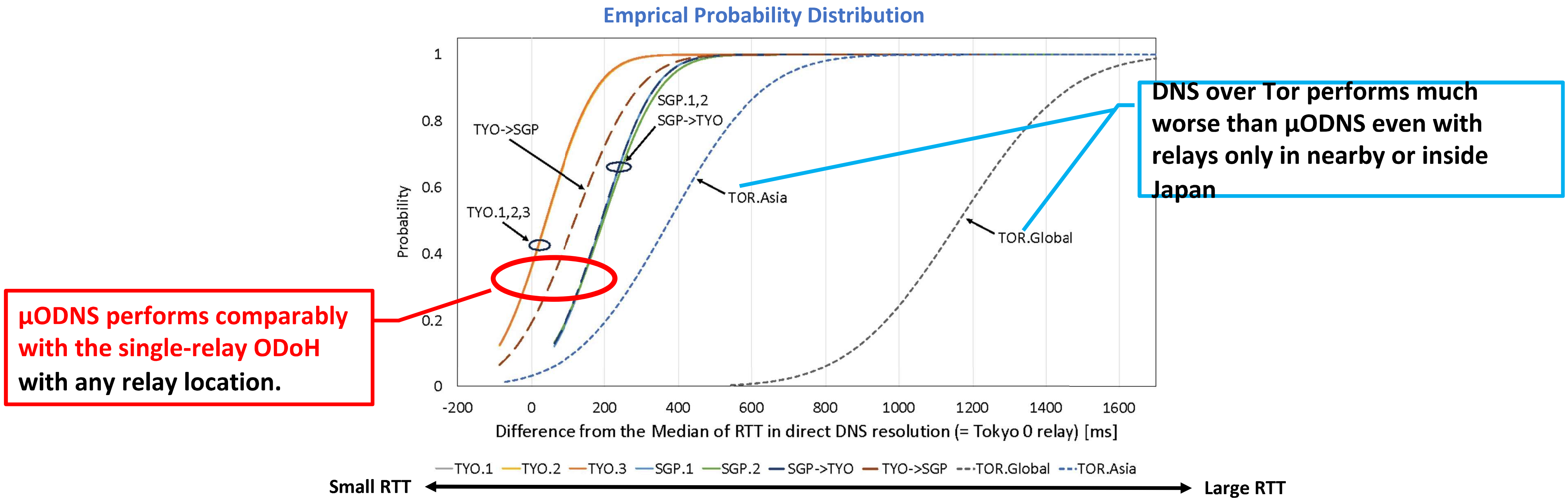
User *B* and this relay colluding with *X* receive encrypted queries from A's trusted relay, **which was randomly mixed with ones from User *A* and other users**. (Moreover, those may NOT include queries generated by User *A*)

Contribution: Design and Implementation

- **Designed the μODNS over HTTPS (μODoH)** by extending the spec of Oblivious DNS over HTTPS (ODoH) with Mix-Net approach, and **showed its probabilistic anonymity in the presence of colluded nodes.**
- **Released μODoH open source software**, and currently **running a testbed** by connecting several organizations.

Contribution: Performance Evaluation on the Testbed

Over the testbed, we have evaluated the performance of μODNS over HTTPS (μODoH) in terms of the round-trip time (RTT) for DNS query-response, compared with the single-relay ODoH and DNS over Tor ➔ UX still maintains!



- J. Kurihara, T. Tanaka and T. Kubo, "μODNS: A Distributed Approach to DNS Anonymization with Collusion Resistance," Computer Networks, Elsevier, vol. 237, p. 110078, Dec. 2023.

Future and On-Going Works for Faster Anonymized DNS

- Design and implementation of a new anonymized protocol with no relay
- New DNS message compression and aggregation technique μODoH's on the encryption layer

- K. Nakano, J. Kurihara and T. Tanaka, "Extensive Study on the Security of Private Information Delivery from Coded Storage," to appear in IEICE Trans. Fundamentals, Mar. 2026.
- R. Aoshima, J. Kurihara and T. Tanaka, "Aggregable Generalized Deduplication," in Proc. ISITA 2024, Nov. 2024.

Close Collaboration Between US and Japan

Yearly project meetings hosted at UC Riverside (Aug 2025, March 2024, Jan 2023)

Weekly online meetings with PIs and students

Valuable exchanges of technical knowledge, close collaboration on posters, conference and journal papers

Dissemination of Project Achievements: Summary

- Publications so far:

1. Toru Hasegawa, Yuki Koizumi, Junji Takemasa, Jun Kurihara, Timothy Wood, and K. K. Ramakrishnan. "Leveraging Heterogeneous Programmable Data Planes for Security and Privacy of Cellular Networks, 5G & Beyond" IEICE Transactions, 2025.
2. Cuidi Wei, Shaoyu Tu, Toru Hasegawa, Yuki Koizumi, K. K. Ramakrishnan, Junji Takemasa, and Timothy Wood. "Envisioning a Unified Programmable Dataplane to Monitor Slow Attacks." IEEE ICNP Workshop Intelligent Classification of High-Speed Network Traffic, 2024.
3. Yutaro Yoshinaka, Mio Kochiyama, Yuki Koizumi, Junji Takemasa, Toru Hasegawa, "A lightweight anonymity protocol at terabit speeds on programmable switches," Elsevier Computer Networks, 2024.
4. Yutaro Yoshinaka, Kanta Tamura, Mio Kochiyama, Yuki Koizumi, Junji Takemasa, Toru Hasegawa, "Toward Terabit-Scale Anonymous Communication Leveraging Programmable Switches," SC2024 Network Research Exhibition, Nov. 2024.
5. Kanta Tamura, Yuki Koizumi, Junji Takemasa, and Toru Hasegawa, "Poster: Toward an Optimal Implementation of ChaCha20-Poly1305 for SmartNICs," IEEE ICNP Poster, Oct. 2024.
6. Cuidi Wei, Shaoyu Tu, Toru Hasegawa, Yuki Koizumi, K. K. Ramakrishnan, Junji Takemasa, and Timothy Wood. "Poster: A Fast Monitor for Slow Network Attacks." In 2024 IEEE Cloud Summit, 153–56. Washington, DC, USA: IEEE, 2024. https://doi.org/10.1109/Cloud-Summit61220.2024.00032.
7. Jun Kurihara, Toshiaki Tanaka and Takeshi Kubo, "µODNS: A Distributed Approach to DNS Anonymization with Collusion Resistance," Computer Networks, Elsevier, vol. 237, p. 110078, Dec. 2023.
8. Kentaro Kita, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, "Secure Middlebox Channel over TLS and its Resiliency against Middlebox Compromise," in Proceedings of IEEE INFOCOM 2023, May 2023.
9. Cuidi Wei, Ahan Kak, Nakjung Choi, and Timothy Wood, "Towards a Scalable 5G RAN Central Unit," in Proceedings IEEE INFOCOM 2023 Workshop on Next-generation Open and Programmable Radio Access Networks (NG-OPERA), May 2023
10. Ryu Watanabe, Ayumu Kubota, and Jun Kurihara, "Application of Generalized Deduplication Techniques in Edge Computing Environments," to Appear in Proceedings of AINA 2023 (M2EC-2023), Juiz de Fora, Brazil, Mar. 2023.
11. Yutaro Yoshinaka, Junji Takemasa, Yuki Koizumi, Toru Hasegawa, "Design and analysis of lightweight anonymity protocol for host- and AS-level anonymity ," Computer Networks, Volume 222, 109559-109559, Feb. 2023.
12. S. Panda, K. K. Ramakrishnan and L. N. Bhuyan, "Synergy: A SmartNIC Accelerated 5G Dataplane and Monitor for Mobility Prediction," 2022 IEEE 30th International Conference on Network Protocols (ICNP), Lexington, KY, USA, 2022.