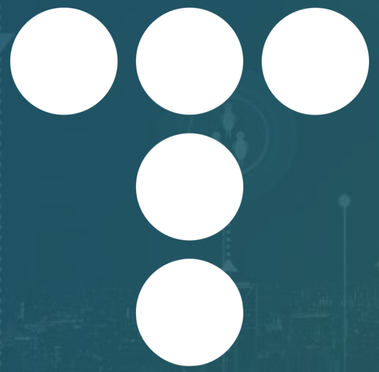

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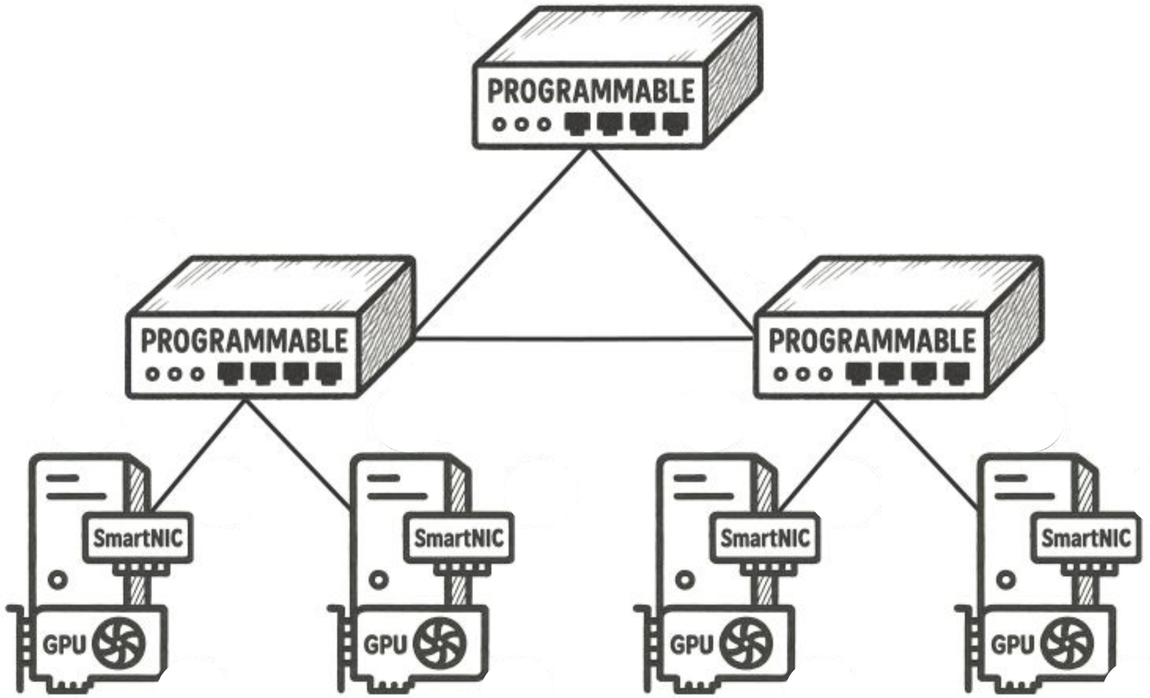
Programmable Hardware Emulation Environment for Realistic and Scalable Network Testing

Fabricio Rodriguez
Telefonica Research

Francisco Germano Vogt
Universidade Estadual de Campinas (UNICAMP)

P4 Developer Days 🕒 (10-Dec, 2025)

Context



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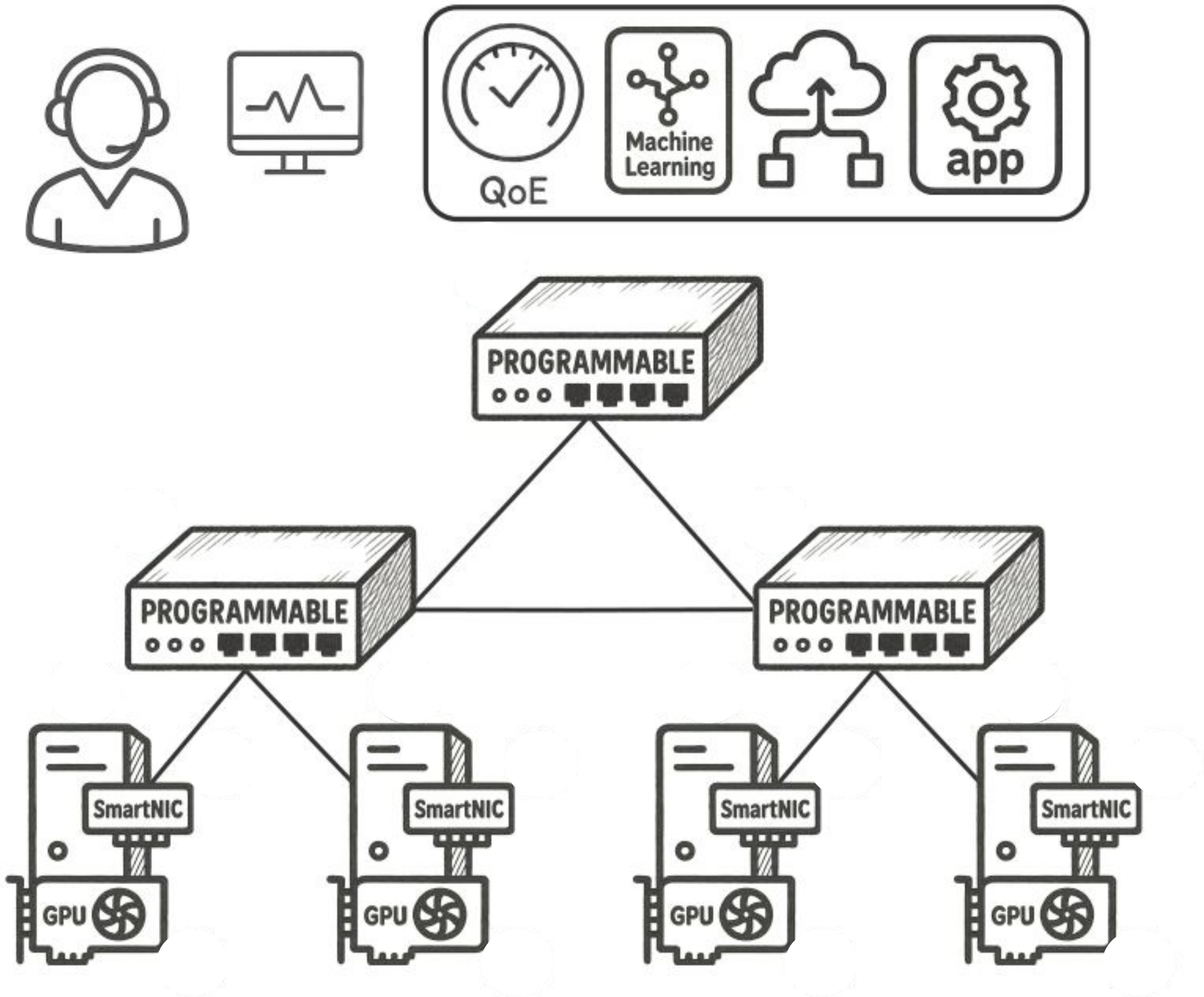

P4 Developer Days 🕒 (10-Dec, 2025)

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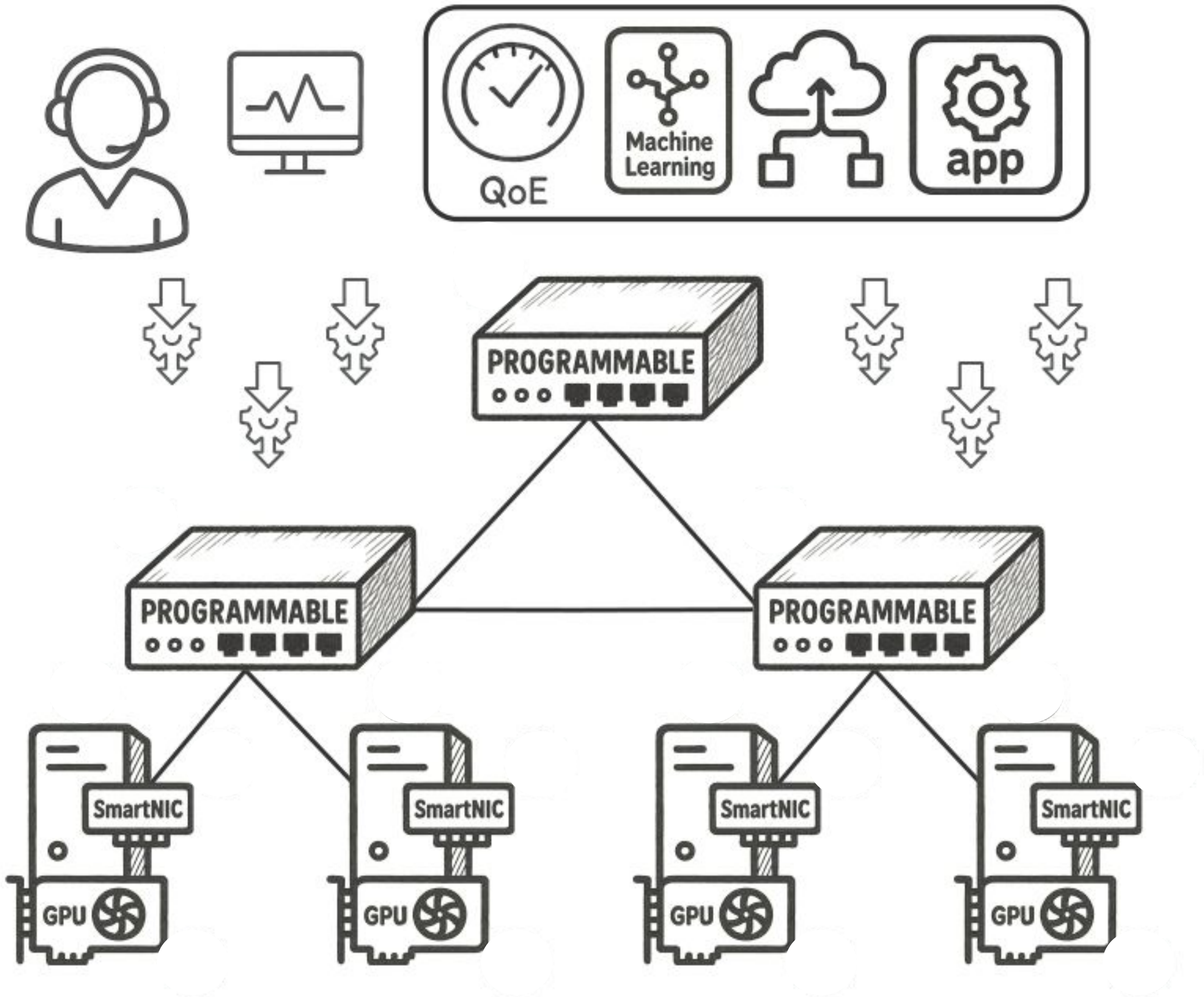

P4 Developer Days (10-Dec, 2025)

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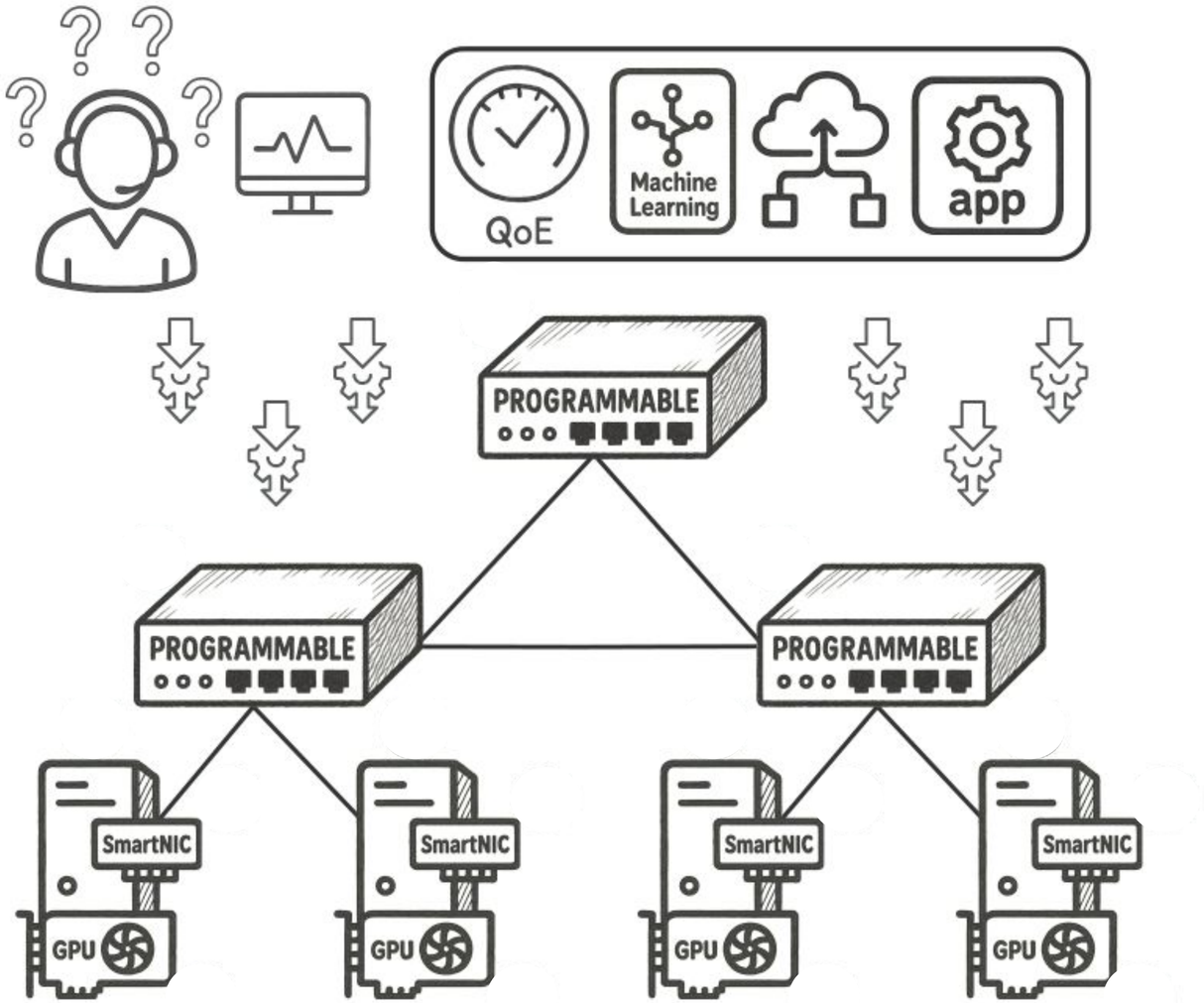

P4 Developer Days 🕒 (10-Dec, 2025)

Context

Fidelity and Scalability: Experiments must combine high fidelity (running on real hardware and devices) with scalability (supporting the size and complexity of real-world topologies, such as data centers).

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P4 Developer Days 🕒 (10-Dec, 2025)

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Scalable Programmable Infrastructure for Network Experimentation

P4 Developer Days 🕒 (10-Dec, 2025)

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Scalable Programmable Infrastructure for Network Experimentation

Can we solve all these challenges?

P4 Developer Days 🕒 (10-Dec, 2025)

Context

Fidelity and Scalability: Experiments must combine high fidelity (running on real hardware and devices) with scalability (supporting the size and complexity of real-world topologies, such as data centers).

- **Up to 15x for switches and 8x for SmartNICs**

Reproducibility: Ensuring that experiments and results can be reproduced by other researchers, while also enabling the reproduction and validation of prior work.

- **Platform able to emulate customized topologies according to the specification**

Fault and Event Injection: Introducing controlled and reproducible faults or events (e.g., packet loss, delay, congestion) is challenging on real hardware platforms.

- **Ability to introduce network metrics like latency/losses in a scripted way**

Scalable Programmable Infrastructure for Network Experimentation

Can we solve all these challenges?

No, but it will help advance in that direction!

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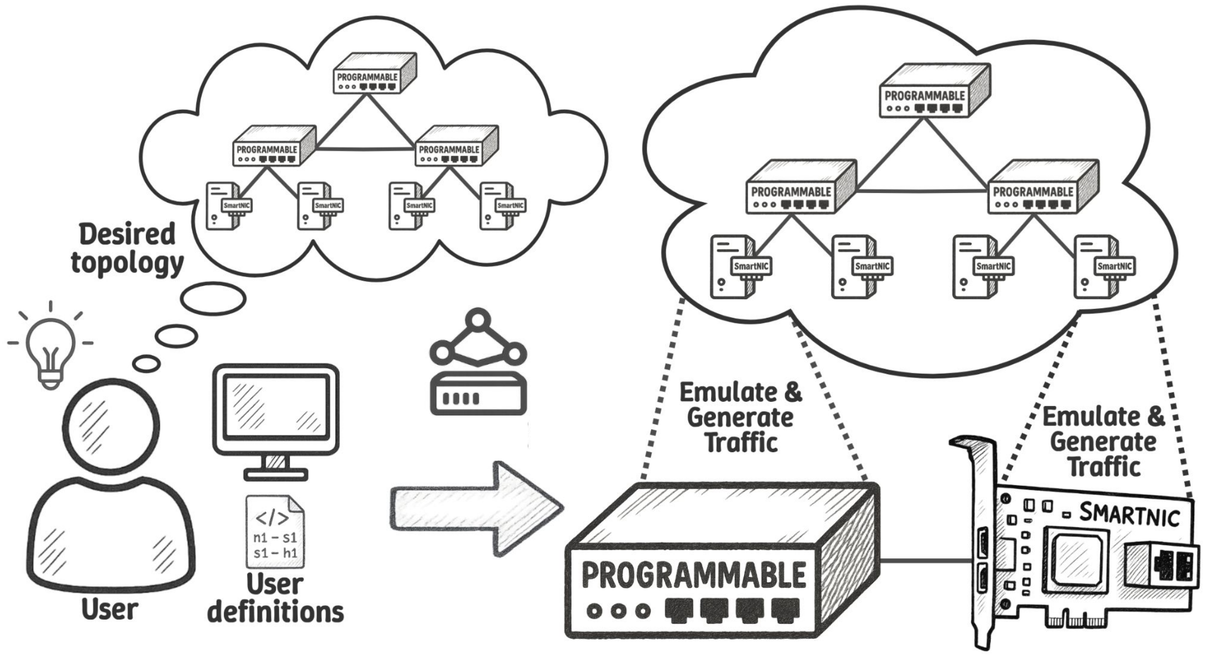
Overview



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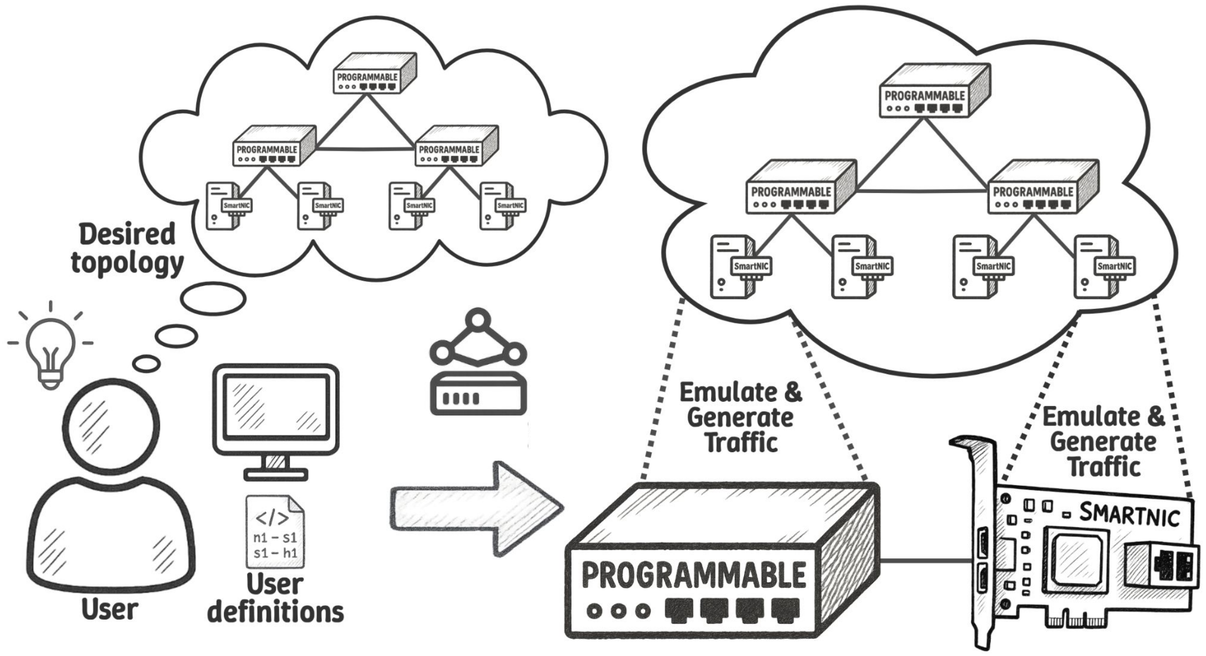
Overview



Available features:

- Switch emulation;
  - User-defined P4 Codes
- SmartNIC emulation;
  - User-defined DOCA applications
- Links emulation;
- Link metrics/events:
  - Latency (fixed);
  - Jitter (fixed and model);
  - Packet loss (fixed and model);
  - Bandwidth (fixed);
- Traffic generation:
  - Up to 8 different flows, supporting different protocols and IPGs.

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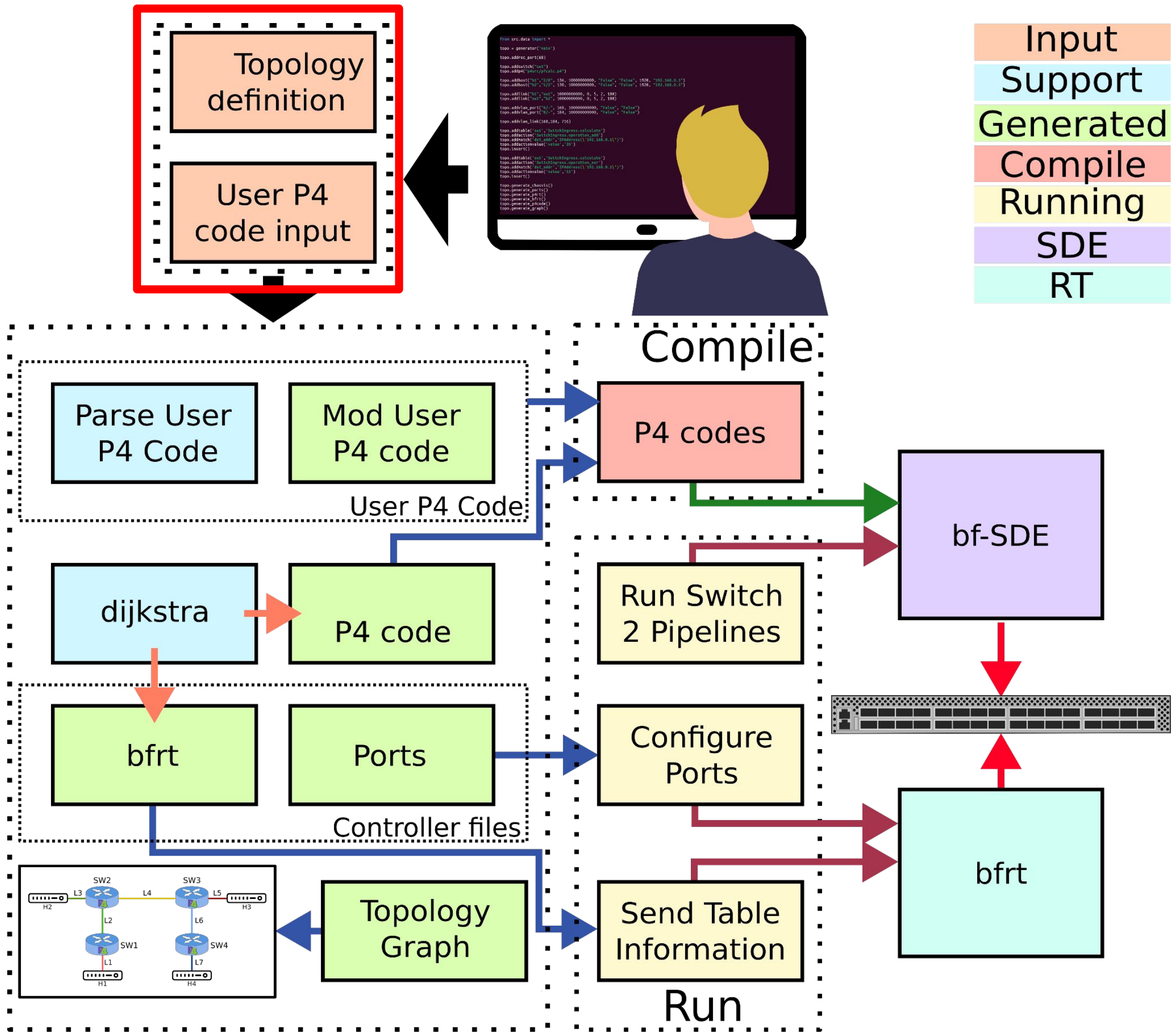
Architecture



The user defines the topology and sets a custom P4 code.

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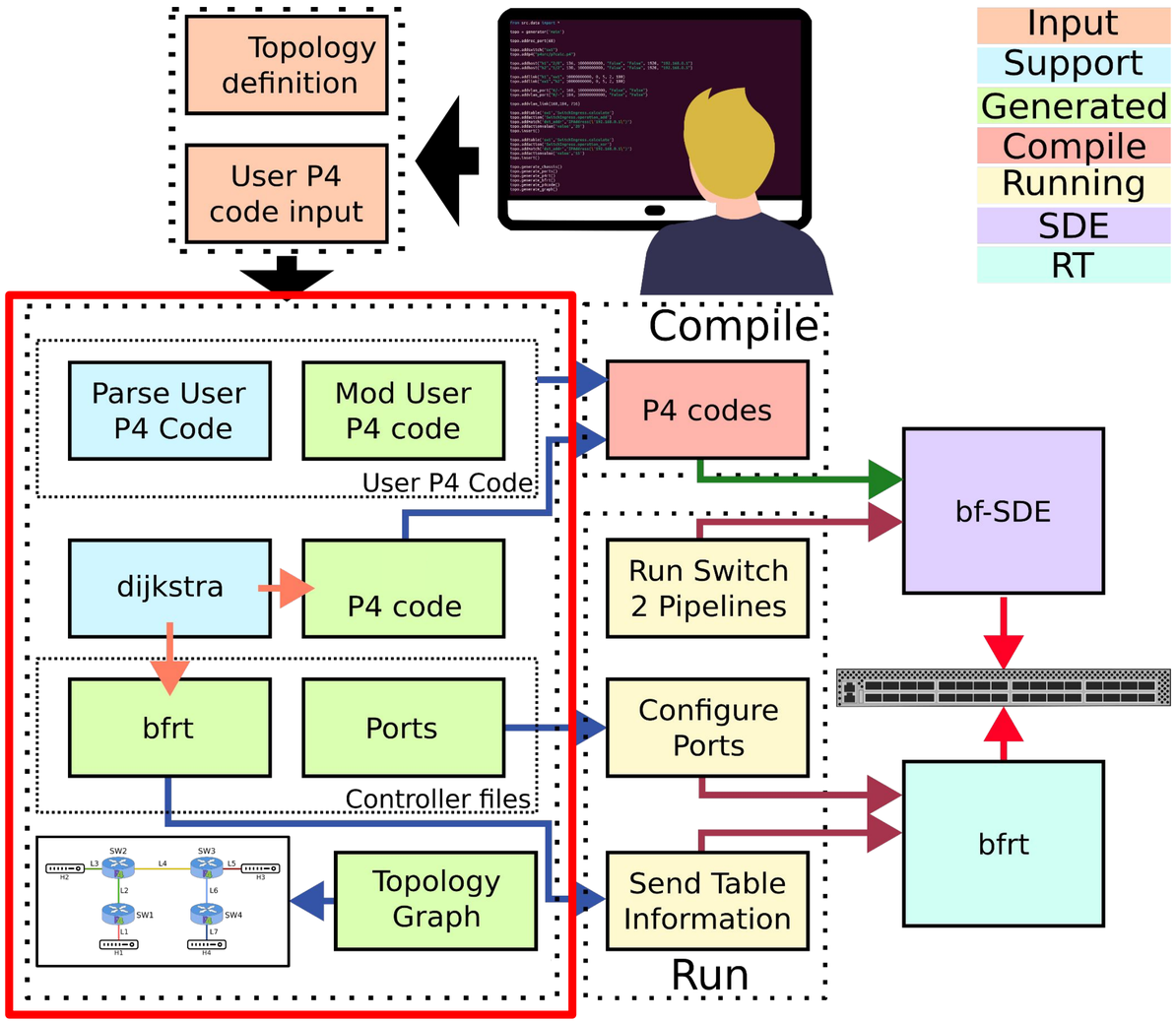
Architecture



The emulator processes the data and generates the necessary files:

- Emulation P4 code
- User P4 code
- Tables information
- Ports configuration

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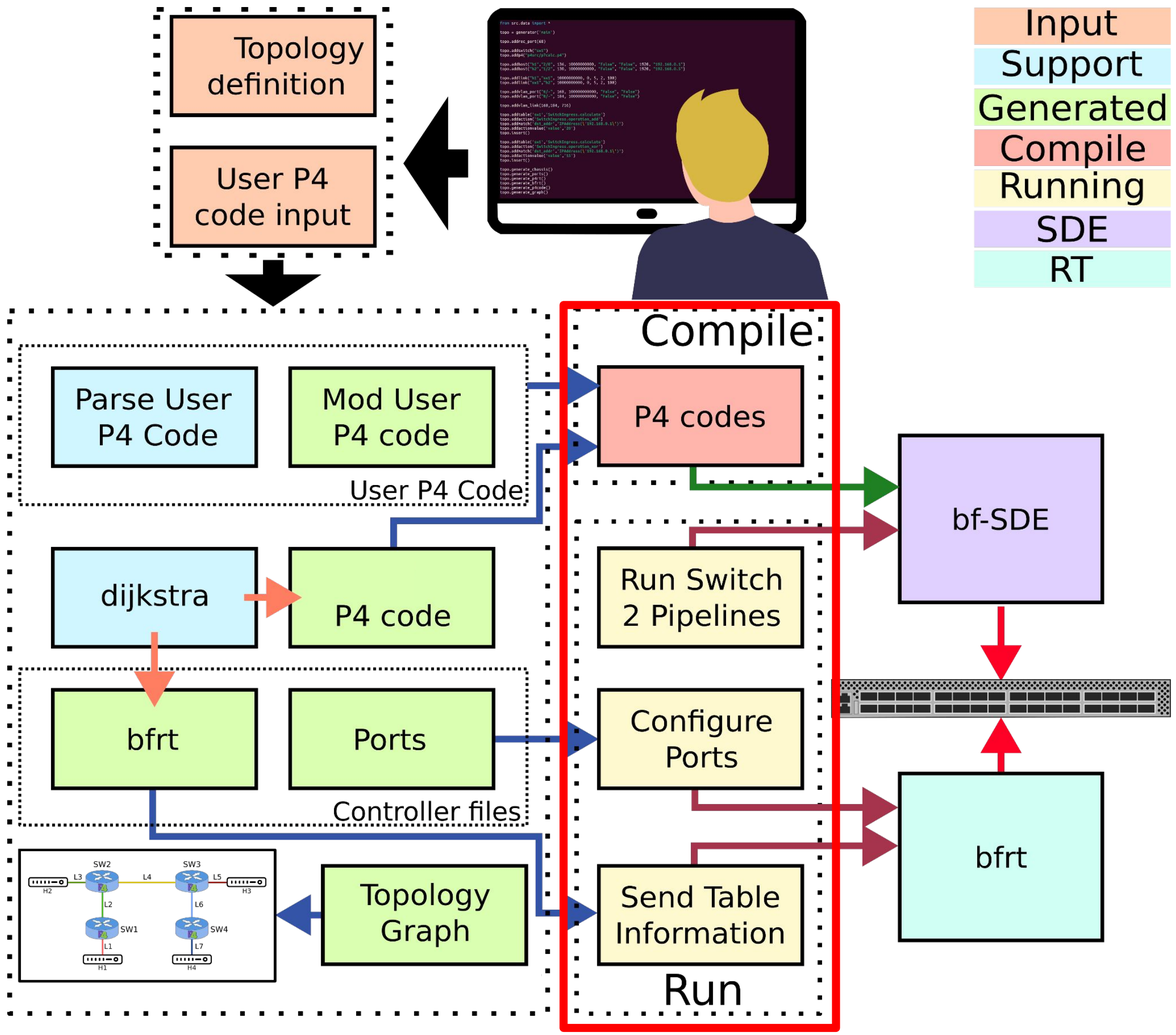
Architecture



Finally, the user can run the switch with both P4 codes and send the tables and ports configuration using the bfrt.

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Switch and links emulation

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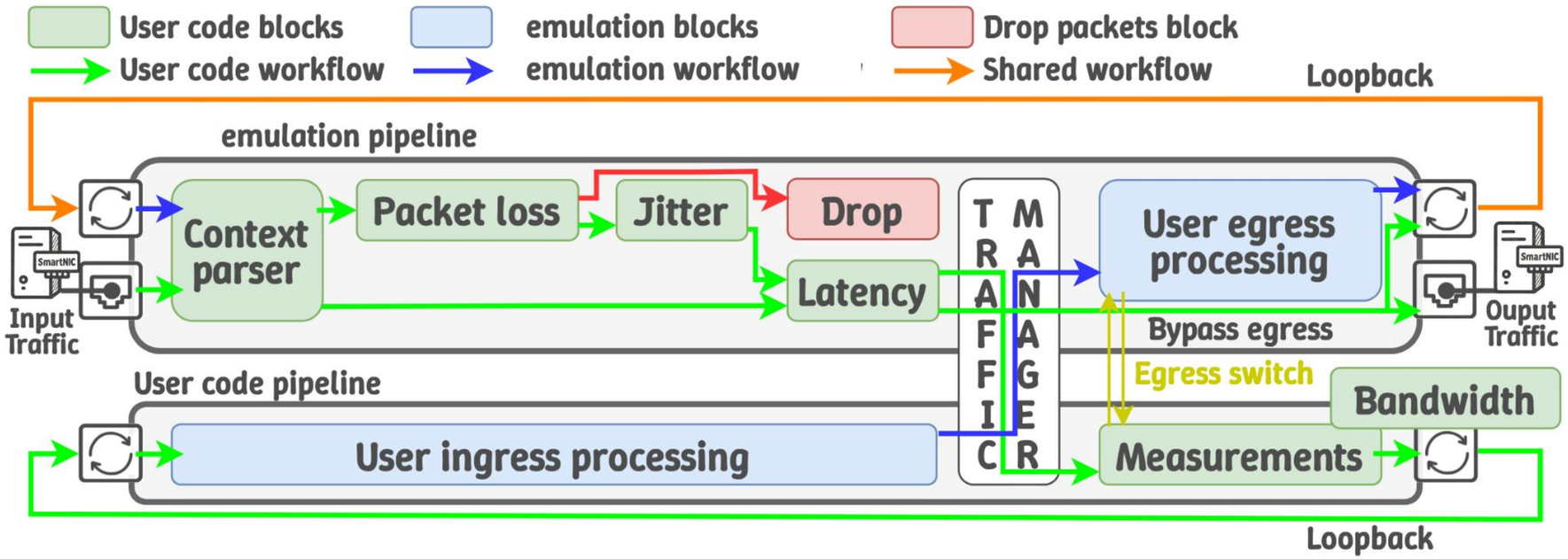
Tofino pipeline:



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Switch and links emulation

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2-Pipes Tofino:

4-Pipes Tofino:

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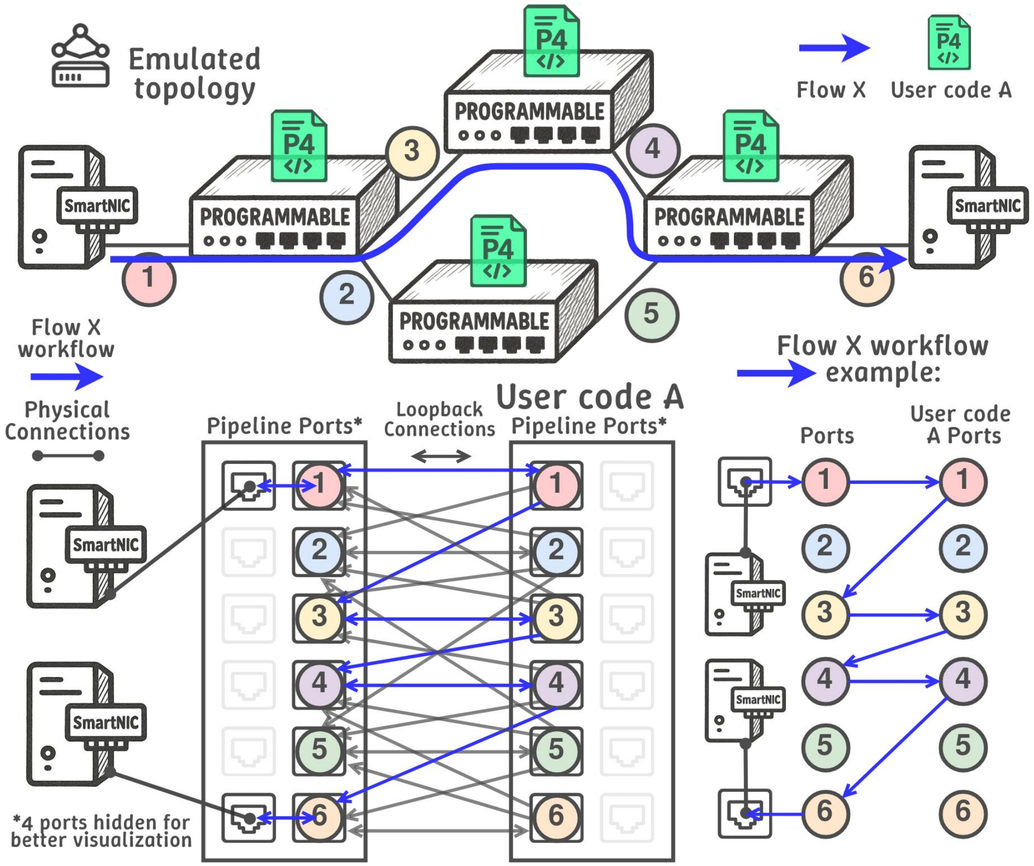
Switch and links emulation

2-Pipes Tofino:



4-Pipes Tofino:

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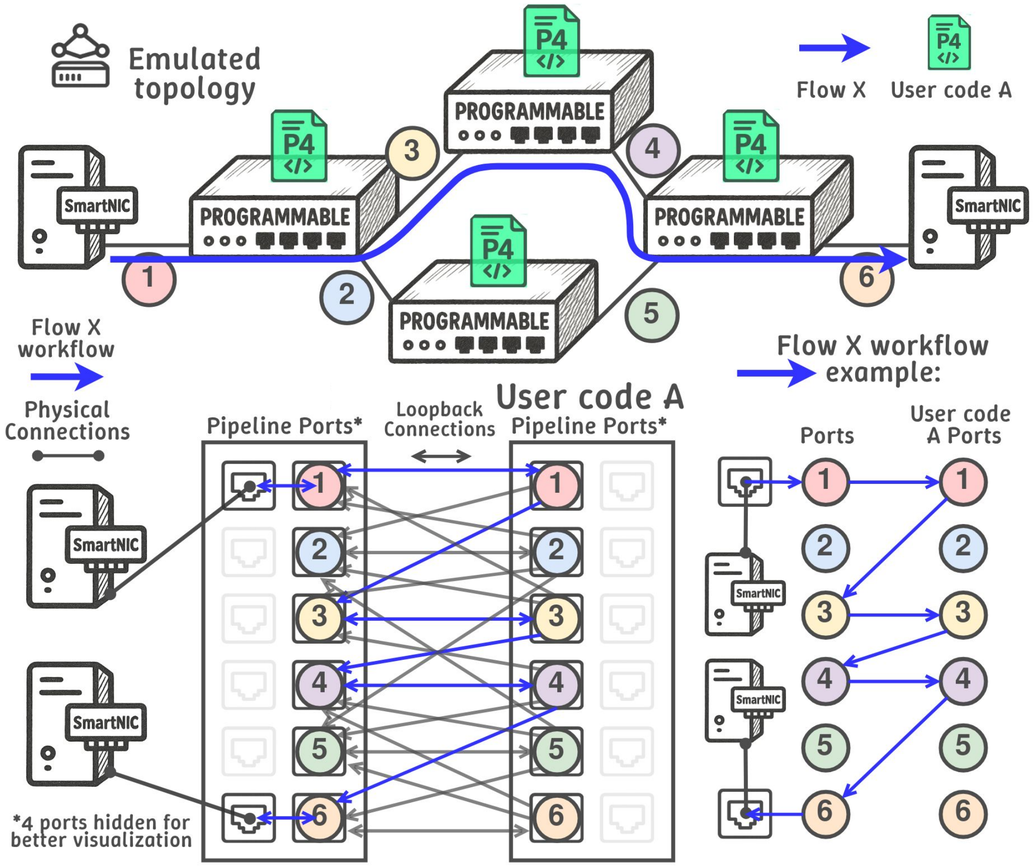
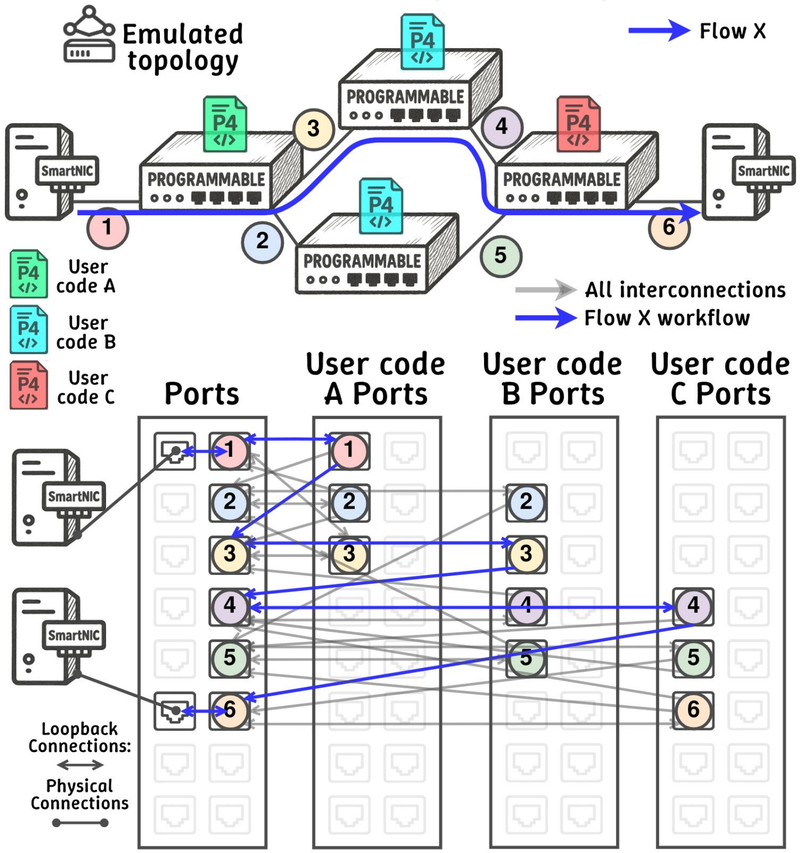
Switch and links emulation

2-Pipes Tofino:



4-Pipes Tofino:



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SmartNIC emulation

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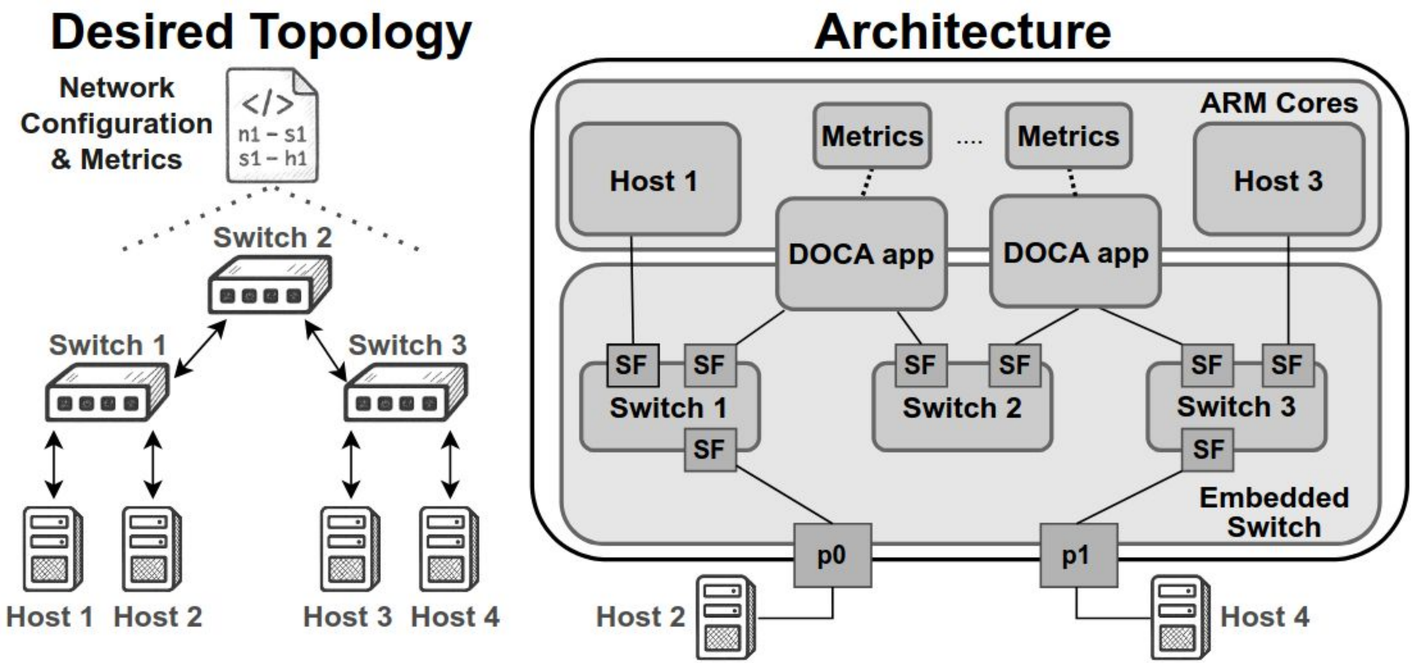
Bluefield-2 pipeline:



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Environment definition

```
from src.data import *

topo = generator('main', sys.argv[1:])

topo.addrec_port(196)
topo.addrec_port_user(68)

topo.addports_file("portConfigs.txt")

topo.tofinoVersion(1) #default is 1

#topo.definePipelines("p1", "spine", "p1", "spine")
topo.definePipelines("p1", "spine")

#Register shift
topo.defineRegisterMaxSize(1000)

topo.addp4("p1", "p4src/simple_forward.p4")

topo.routing(2) #type for user defined routing, 0 for default routing
```

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Environment definition

```
22  # addswitch(name, p4code)
23  topo.addswitch("sw1", "p1")
24  topo.addswitch("sw2", "p1")
25  topo.addswitch("sw3", "p1")
26
27  topo.addhost("h1","5/0", 164, 100000000000, "False", "False", 1920, "192.168.0.10")
28  topo.addhost("h2","6/0", 172, 100000000000, "False", "False", 1920, "192.168.0.20")
29
30  topo.addlink("h1","sw1", 100000000000, 0, 0, 0, 100)
31  topo.addlink("sw1","sw2", 100000000000, 0, 0, 0, 100)
32  topo.addlink("sw2","sw3", 100000000000, 0, 0, 0, 100)
33  topo.addlink("sw3","h2", 100000000000, 0, 0, 0, 100)
```

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Environment definition

```
36    # add table entry sw1
37    topo.addtable('sw1','SwitchIngress.forward')
38    topo.addaction('SwitchIngress.send')
39    topo.addmatch('dst_addr','IPAddress(\'192.168.0.20\')')
40    topo.addactionvalue('port','140')
41    topo.addactionvalue('sw', '1')
42    topo.insert()
43
44
45    # add table entry sw1
46    topo.addtable('sw1','SwitchIngress.forward')
47    topo.addaction('SwitchIngress.send')
48    topo.addmatch('dst_addr','IPAddress(\'192.168.0.10\')')
49    topo.addactionvalue('port','132')
50    topo.addactionvalue('sw', '0')
51    topo.insert()
```

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Implementations and limitations

- We implemented the pre-processing in python, and the switch/SmartNIC codes in P4 and DOCA, respectively.

- Our tool auto-generates all codes/configuration files according to the desired topology.

Limitations:

- The user switch P4 code need to be edited, and has a maximum limit of registers/table entries that it can use.
- Latency and jitter can impact significantly in the throughput.
- DOCA applications are limited to simple applications using a single core.

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Scalability and components limits

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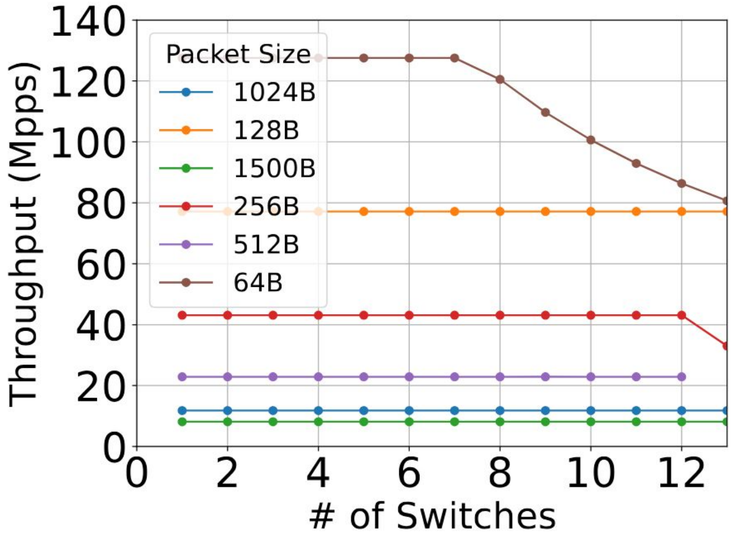
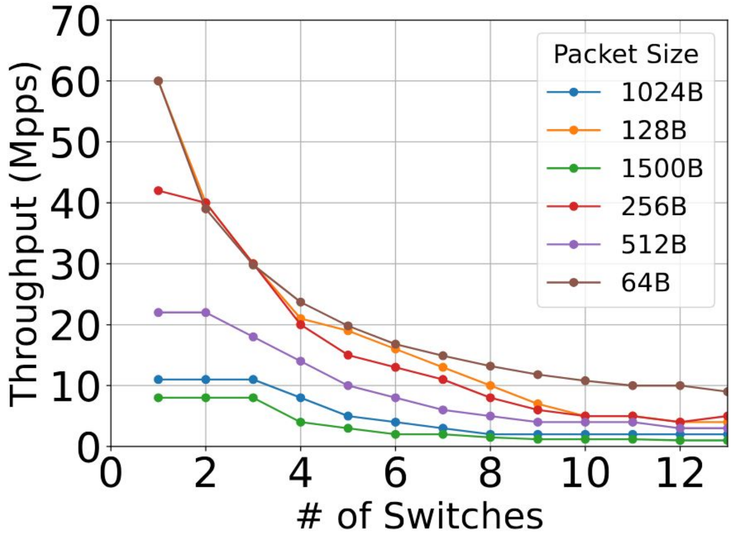
Throughput according to the number of switches and packet sizes:



Tofino



Bluefield-2

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Scalability and components limits

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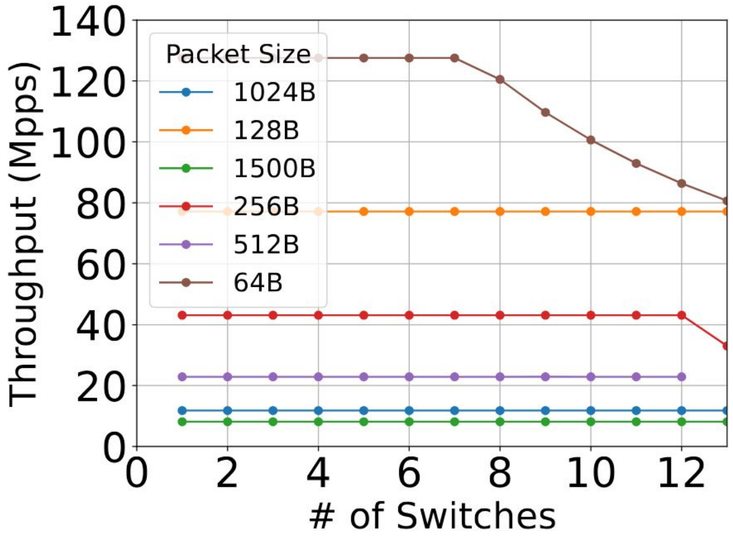

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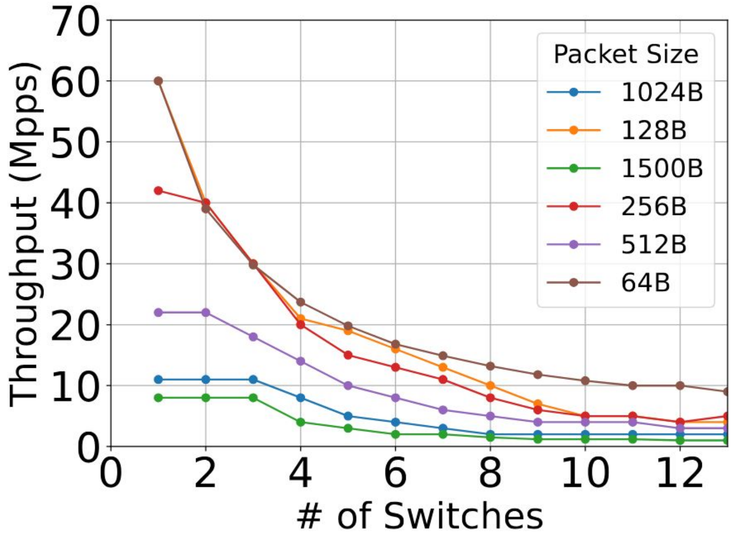
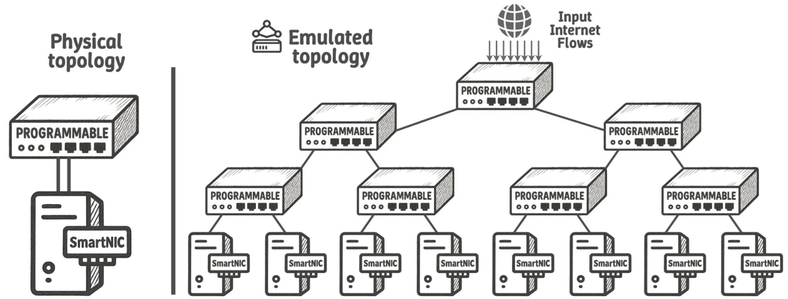


Bluefield-2

Topology to be tested:



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Evaluation goals

Scalability and components limits:

Practical applicability:

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Scalability and components limits:

- Evaluate the performance limits of each functionality (switch and SmartNIC emulation, links and metrics, etc).
- Validate the maximum size topology in different scenarios.

Practical applicability:

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Evaluation goals

Scalability and components limits:

- Evaluate the performance limits of each functionality (switch and SmartNIC emulation, links and metrics, etc).
- Validate the maximum size topology in different scenarios.

Practical applicability:

- Reproduce common examples (simple switch, in-band network telemetry, datacenter topology, etc).
- Reproduce works from recent high-impact conferences and its results in different scenarios:
  - Works that can benefit from increased experiment scale.
  - Works that can benefit from events/metrics insertion.

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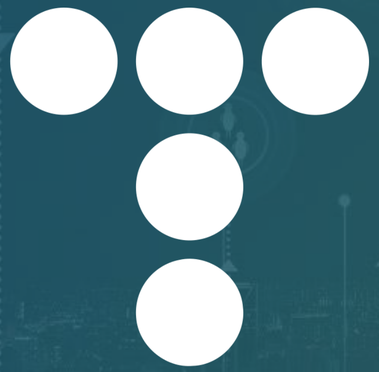
Conclusions

- We introduced a programmable hardware emulation environment that combines Tofino switches and BlueField-2 SmartNICs to emulate realistic, scalable topologies.
- The platform bridges fidelity and scalability, enabling experiments on real hardware while emulating large multi-switch / multi-SmartNIC networks with controllable link metrics (latency, jitter, loss, reordering).
- It auto-generates P4, DOCA and configuration files from a high-level topology description, lowering the barrier to test new in-network applications and data-plane ideas.
- The environment supports reproducible experiments and fault/event injection, which is key to validating prior work and exploring “what-if” scenarios at scale.
- Ongoing work: push larger topologies, richer DOCA apps and more complex traffic/QoE use cases, and open it for collaboration with the P4 community.



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Github Repository:

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