Towards Low-Power and Low Data-Rate Software-Defined Radio Baseband with RISC-V Processor for Flexibility and Security

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Context

Security of embedded systems?

- Physical Access
- Cryptography Implementation
- ...
- Network Entry Point

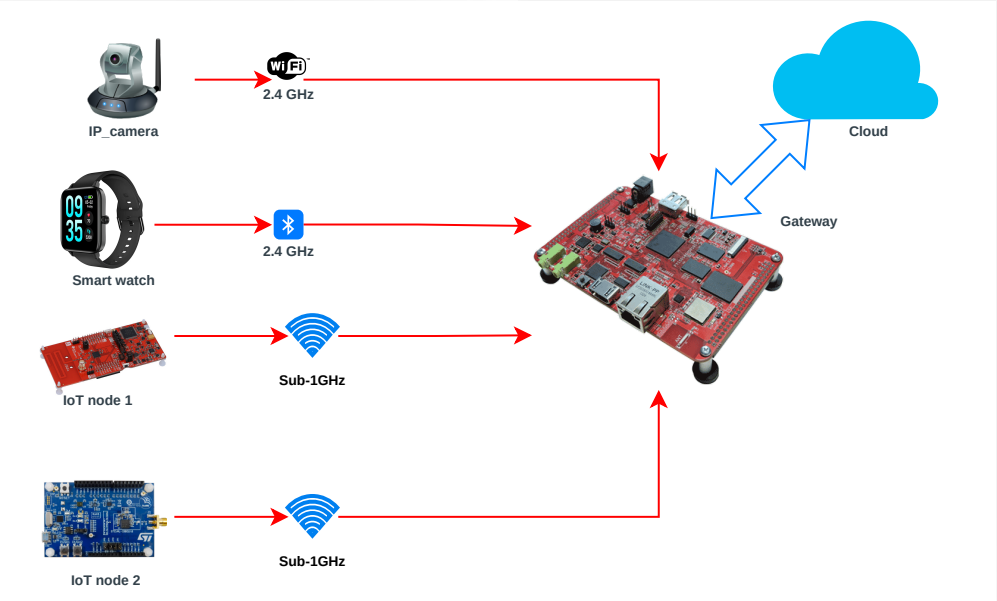

Figure: IoT architecture

SoC for IoT overview

- Main CPU for application user
- Peripherals and connectivity
- Integration of protection mechanism
- Isolation between Radio and user application

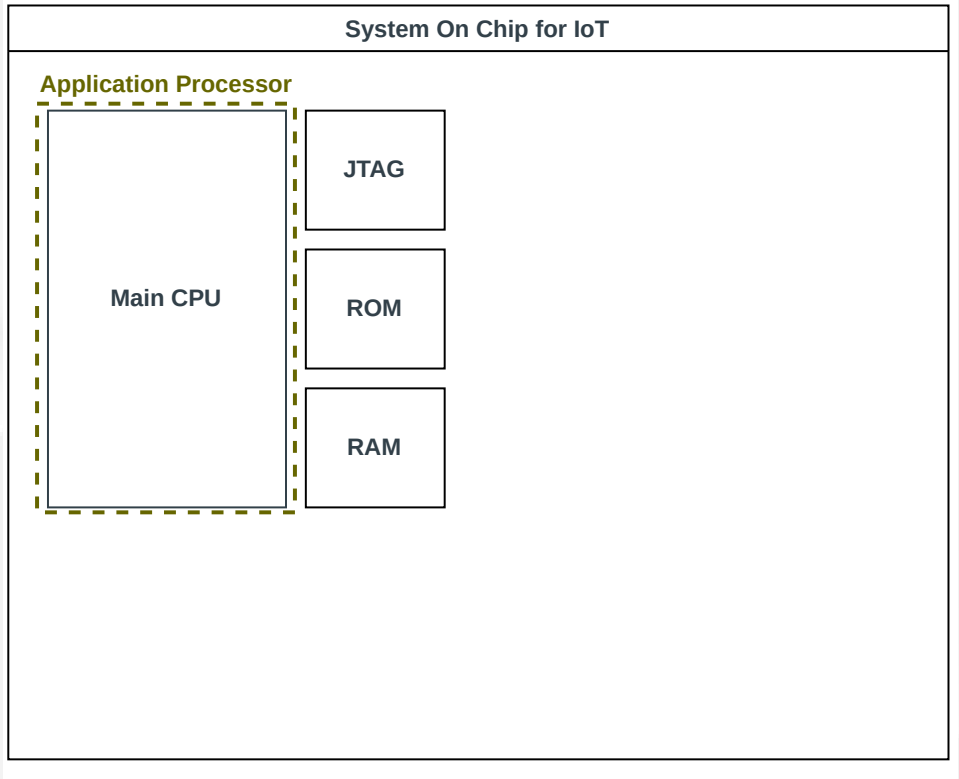

Figure: SoC IoT overview

Don’t forget that SoC are integrating a wireless connectivity unit!

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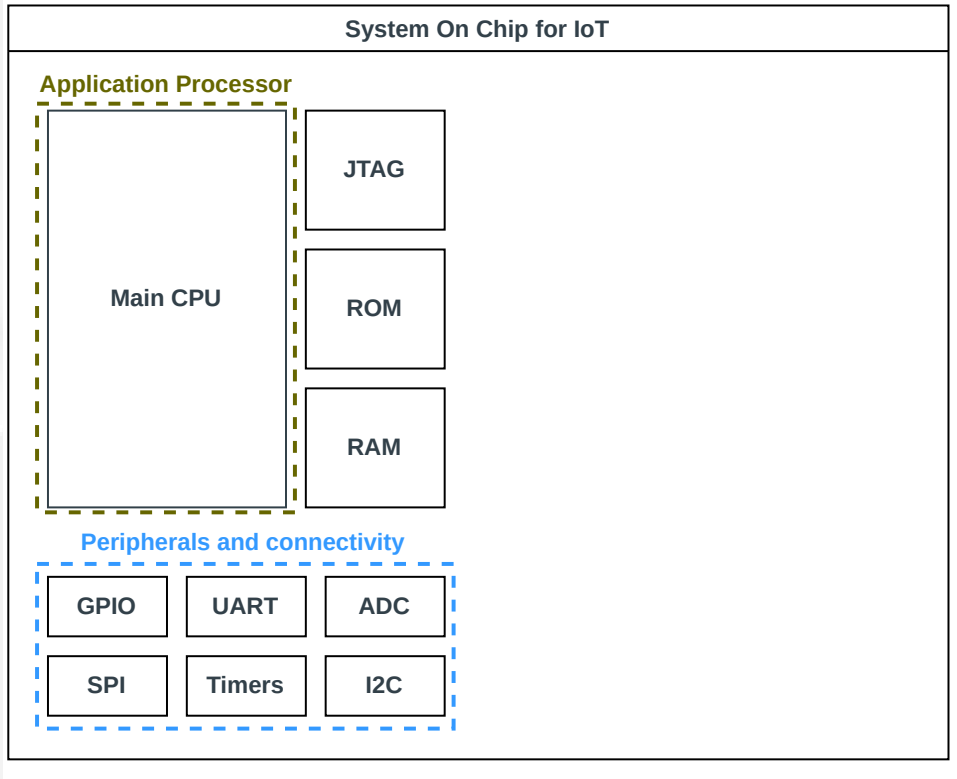

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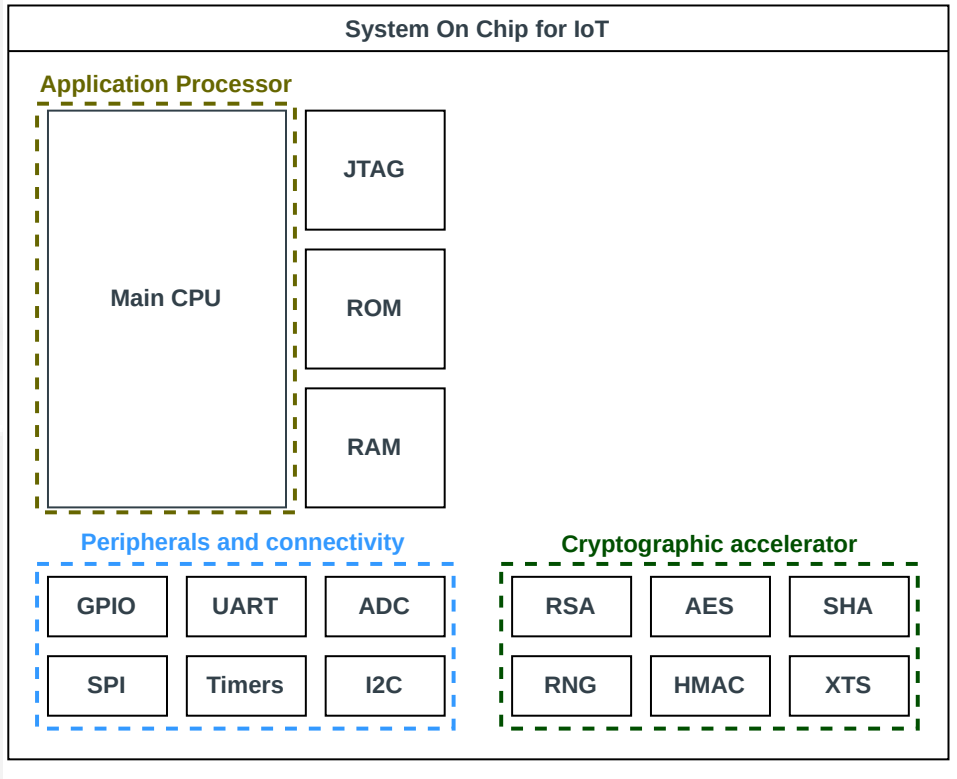

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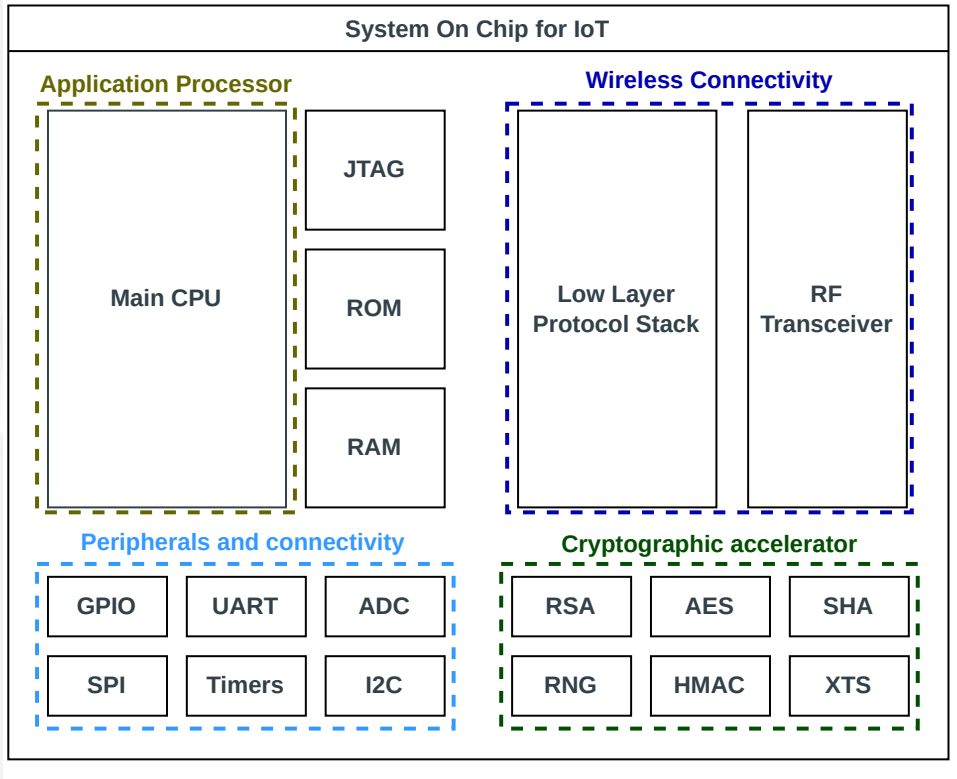


Figure: SoC IoT overview

Don’t forget that SoC are integrating a wireless connectivity unit!

Outline

1. Threat model and countermeasures
2. Proposed security mechanism: a multi-metrics HIDS
3. Test-bed & Evaluation

Outline

1. **Threat model and countermeasures**
   - Threat Model
   - Vulnerabilities in IoT
   - Attack examples
   - Attacks
   - Security mechanisms & mitigation
2. **Proposed security mechanism: a multi-metrics HIDS**
3. **Test-bed & Evaluation**

Threat Model

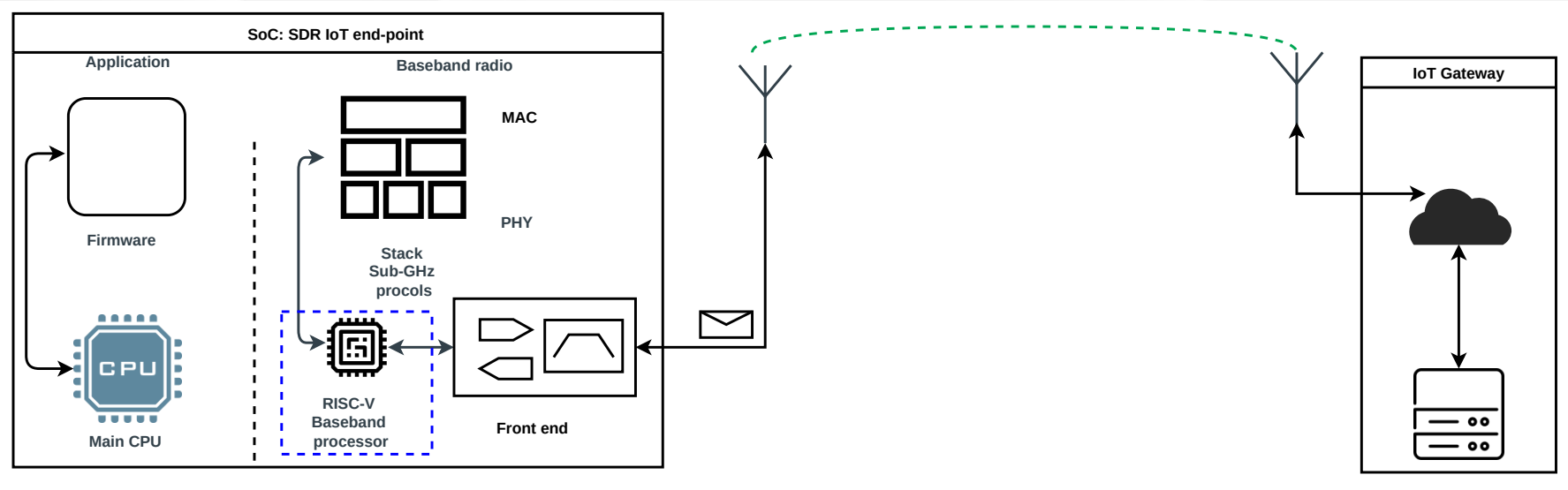
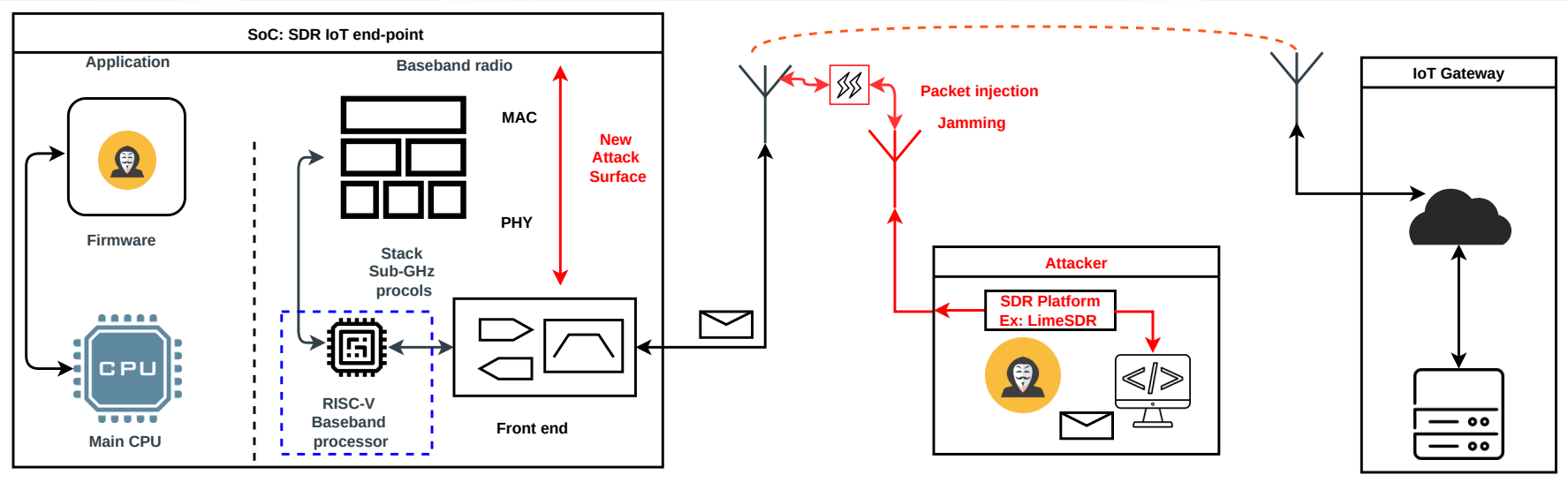


Figure: Potential Threat Model

Target : Remote Attacks

- Jamming Attack
- Logical Attacks: Packet Injection, . . .

Threat Model



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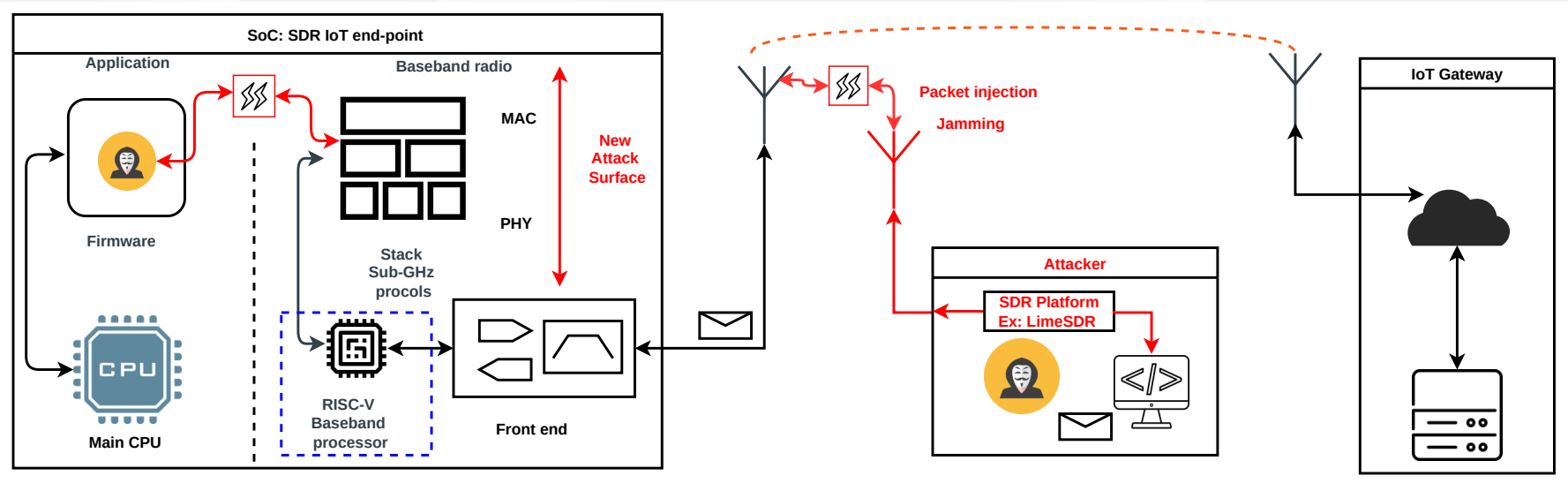

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Vulnerabilities in IoT

Vulnerability	AMNESIA33	BLEEDINGBIT	LoRaDawn
Number of CVEs	33 [Labs, 2020]	2 [Seri, Benn (ARMIS et al., 2019]	2 [ten, 2020]
Where ?	Poor Software Development	Masking Error, OAD	OTAA Process, 32bit Gateway
Target Device	uIP, FNET, picoTCP, NuTNet	AP with TI BLE	LoRaMac-node, LoRa Basics Station
Stack Layer	Physical /MAC	MAC	MAC
Stack / protocol	TCP/IP / IEEE 802.15.4	BLE	LoRaWAN
Exploit	RCE, DoS, Steal Data	Packet injection, RCE	DoS, RCE, Heap UAF

Table: A set of three Groups of vulnerabilities in IoT and their features

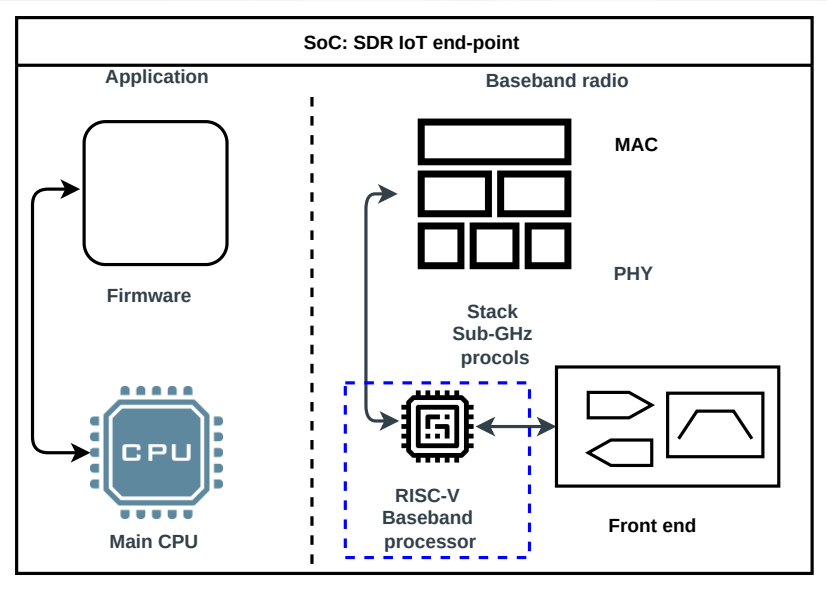

Figure: SoC for IoT with wireless connectivity

Example of Exploit : InjectBLE [Cayre et al., 2021]

- Vulnerabilities: Long synchronization time between Slave and Master BLE in connection step
- Exploit: Packet injection (Hijacking slave and master, MITM)
- InjectBLE Firmware
- Mirage framework
- Used BLE module: nRF52840-dongle

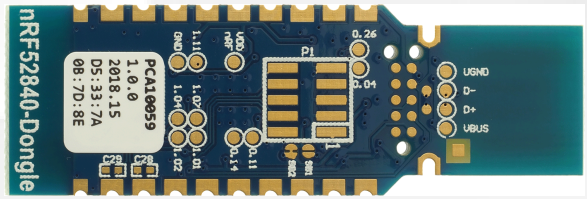

Figure: nRF52840-dongle : `https://www.nordicsemi.com/`

Example of Exploit : Main in the middle (MITM) attack

We reproduce the MITM attack using two modules from mirage framework in order to sniff packets between master and slave: (ble_hijack and ble_maste)

- ble_master: Mobile App
- ble_slave: Led strip
- Attacker: Laptop with nRF52840-dongle

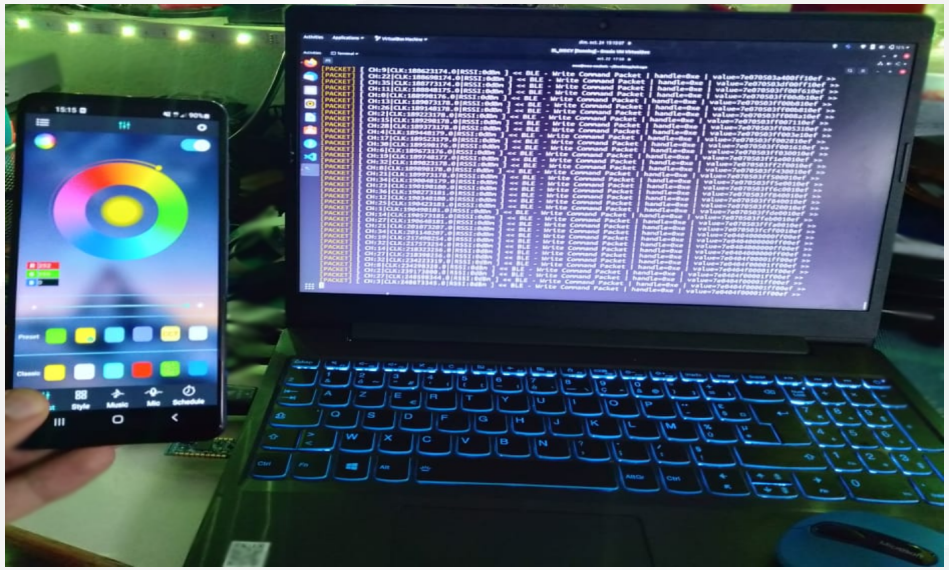

Figure: Sniffing packet exploit

Example of Exploit: Packet Injection

After hijacking the BLE Master we perform a packet injection exploit

```
[PACKET] [ CH:34|CLK:225120999.0|RSSI:0dBm ] << BLE - Find Information Request Packet >>
[PACKET] [ CH:2|CLK:225128729.0|RSSI:0dBm ] << BLE - Find Information Response Packet | format=0x1 | data=0b000229 >>
[PACKET] [ CH:7|CLK:225135999.0|RSSI:0dBm ] << BLE - Read By Type Request >>
[PACKET] [ CH:12|CLK:225143729.0|RSSI:0dBm ] << BLE - Error Response Packet | req=0x8 | handle=0xc | ecode=0xa >>
[PACKET] [ CH:17|CLK:225150999.0|RSSI:0dBm ] << BLE - Read By Type Request >>
[PACKET] [ CH:22|CLK:225158729.0|RSSI:0dBm ] << BLE - Read By Type Response | data=070d00060e00f3ff0f00101000f4ff >>
[PACKET] [ CH:27|CLK:225165999.0|RSSI:0dBm ] << BLE - Read By Type Request >>
[PACKET] [ CH:5|CLK:225188729.0|RSSI:0dBm ] << BLE - Error Response Packet | req=0x8 | handle=0x10 | ecode=0xa >>
[PACKET] [ CH:10|CLK:225195999.0|RSSI:0dBm ] << BLE - Find Information Request Packet >>
[PACKET] [ CH:20|CLK:225211229.0|RSSI:0dBm ] << BLE - Error Response Packet | req=0x4 | handle=0x11 | ecode=0xa >>
[PACKET] [ CH:25|CLK:225218499.0|RSSI:0dBm ] << BLE - Control PDU Packet | type=LL_CONNECTION_UPDATE_REQ | data=01000024000000f4012f00 >>
[PACKET] [ CH:23|CLK:225308499.0|RSSI:0dBm ] << BLE - Read Request Packet | handle=0xe >>
[PACKET] [ CH:1|CLK:225443731.0|RSSI:0dBm ] << BLE - Read Response Packet | value=454c4b39364b335232345632363400000000000 >>
[PACKET] [ CH:6|CLK:225488500.0|RSSI:0dBm ] << BLE - Write Command Packet | handle=0xe | value=7e07830f321800ffef >>
[PACKET] [ CH:4|CLK:227468745.0|RSSI:0dBm ] << BLE - Connection Parameter Update Request Packet | slaveLatency=1 | timeoutMult=100 | minInterval=40 | maxInterval=6
0 >>
[PACKET] [ CH:9|CLK:227513514.0|RSSI:0dBm ] << BLE - Control PDU Packet | type=LL_CONNECTION_UPDATE_REQ | data=0100003c00010064006700 >>
[INFO] Starting Master Hijacking attack: injecting LL_CONNECTION_UPDATE_REQ...
[SUCCESS] Injection successful after 2 attempts !
[INFO] Waiting for connection update instant...
[SUCCESS] Attack successful !
[INFO] SubInterface available: butterfly0:sub0 (master)
[INFO] Instantiating subdevice :butterfly0:sub0
[MASTER|0xe4773f5d]: write_cmd 0xe 7e070503ff00c110ef
[SUCCESS] Write Command : handle = 0xe / value = 7e070503ff00c110ef
[MASTER|0xe4773f5d]: write_cmd 0xe 7e070503ff00c110ee
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[MASTER|0xe4773f5d]: write_cmd 0xe 7e070503002aff10ef
[SUCCESS] Write Command : handle = 0xe / value = 7e070503002aff10ef
[MASTER|0xe4773f5d]: write_cmd 0xe 7e070503ff00c110ef
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[SUCCESS] Write Command : handle = 0xe / value = 7e070503002aff10ef
[MASTER|0xe4773f5d]:
```
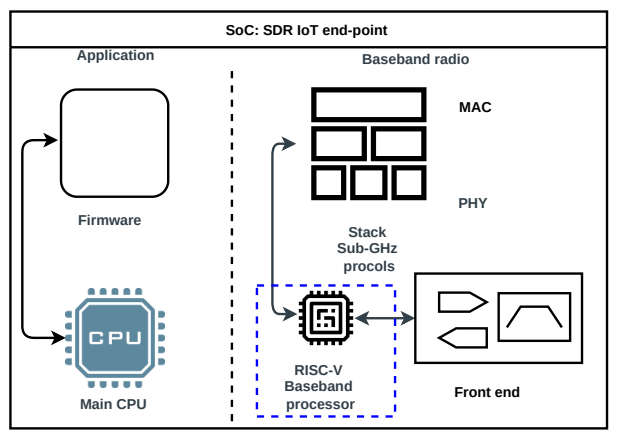

Figure: Packet Injection exploit

Attacks in IoT



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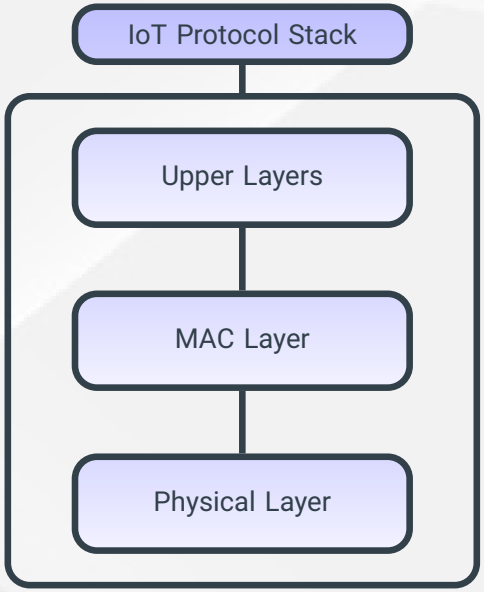

Figure: IoT protocol stack layers

E (Exploited Layer) **T** (Targeted Layer)

Ref	Protocol	Attack	PHY	MAC	Upper	Exploit
[Cayre et al.,]	Zigbee	Wazabee	E	E/T	T	DoS, packet injection
[Aras et al.,]	LoRaWAN	Selective Jamming	E	E/T	T	DoS, Wormhole
[Hessel et al.,]	LoRaWAN	Spoofing	E	E/T	-	DoS
[Avoine and Ferreira, 2018]	LoRaWAN		-	T	T	replay, decrypt, DoS
[Cayre et al., 2021]	BLE	InjectBLE	E	E/T	T	MITM, Sniffing
[Zhang et al., 2020]	BLE	Downgrade	-	-	T	DoS, MITM
[Santos et al., 2019]	BLE	Injection-free	-	-	E/T	DoS, MITM
[Antonioli et al., 2020]	BT/BLE	Key.nego downgrade	-	E/T	E/T	Decypt packet, MITM

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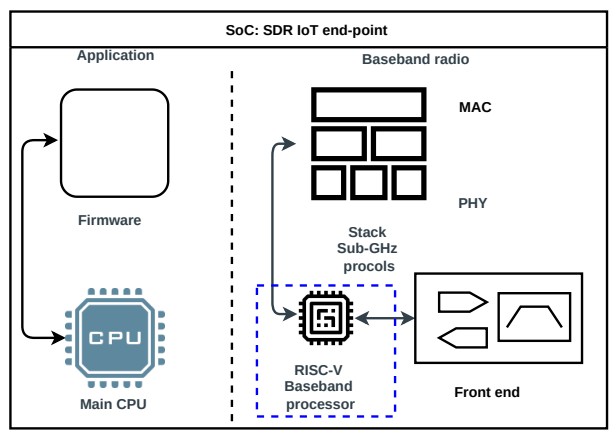
Attacks in IoT



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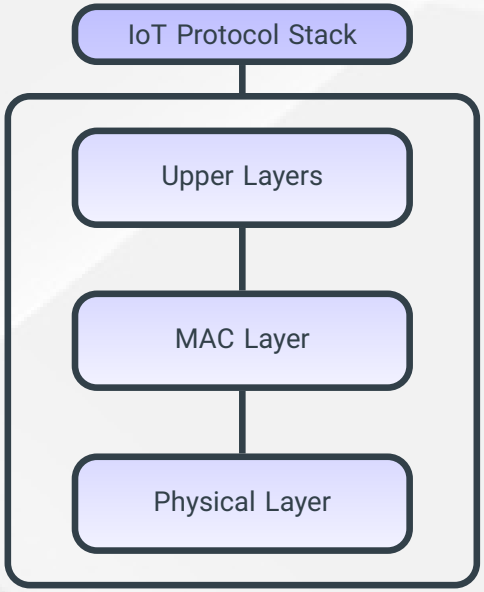

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Security mechanisms & mitigation

Features	CC1356	CC1352R1	STM32WL54CC
Sec. Boot (protection)	✓	✓	✓
Cryptography (protection)	✓	✓	✓
OTA (Update)	✓	✓	✓
Heap ASLR (protection)	✗	✗	✗
Monitoring (detection)	✗	✗	✗
DIFT (hard. monitor)	✗	✗	✗
Code instrumentation (protection)	✗	✗	✗
Anomaly/Intrusion detection	✗	✗	✗

Table: Platform security features comparison

Security Mechanisms

- Confidentiality, Integrity and availability
- Protection mechanisms
- Update & Over the air Mechanisms
- Monitoring & Detection Mechanisms

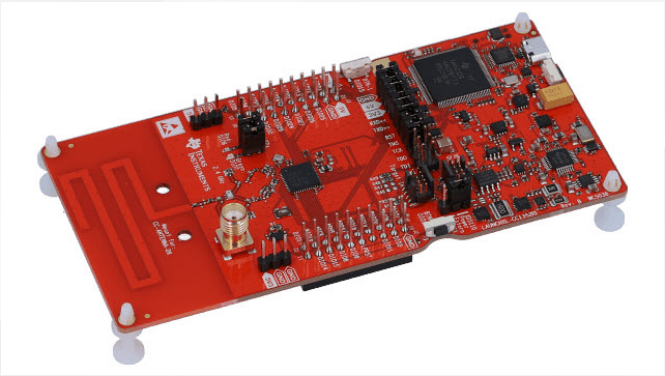

Figure: CC1352R1 : SoC for IoT

Outline

1. Threat model and countermeasures
2. **Proposed security mechanism: a multi-metrics HIDS**
   - Motivation and contribution
   - Intrusion Detection System Taxonomy
   - Host based IDS in state of the art
   - Towards a multi-level metrics HIDS
3. Test-bed & Evaluation

Motivation and contribution

Motivation

- Remote attacks detection on wireless connectivity of IoT SoC
- The necessity of a monitoring detection mechanism that captures system behavior and identifies attacks.

Contribution: Intrusion Detection System (IDS)

- Acquisition, Analyze and Identification, warn or block attacks

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IDS taxonomy

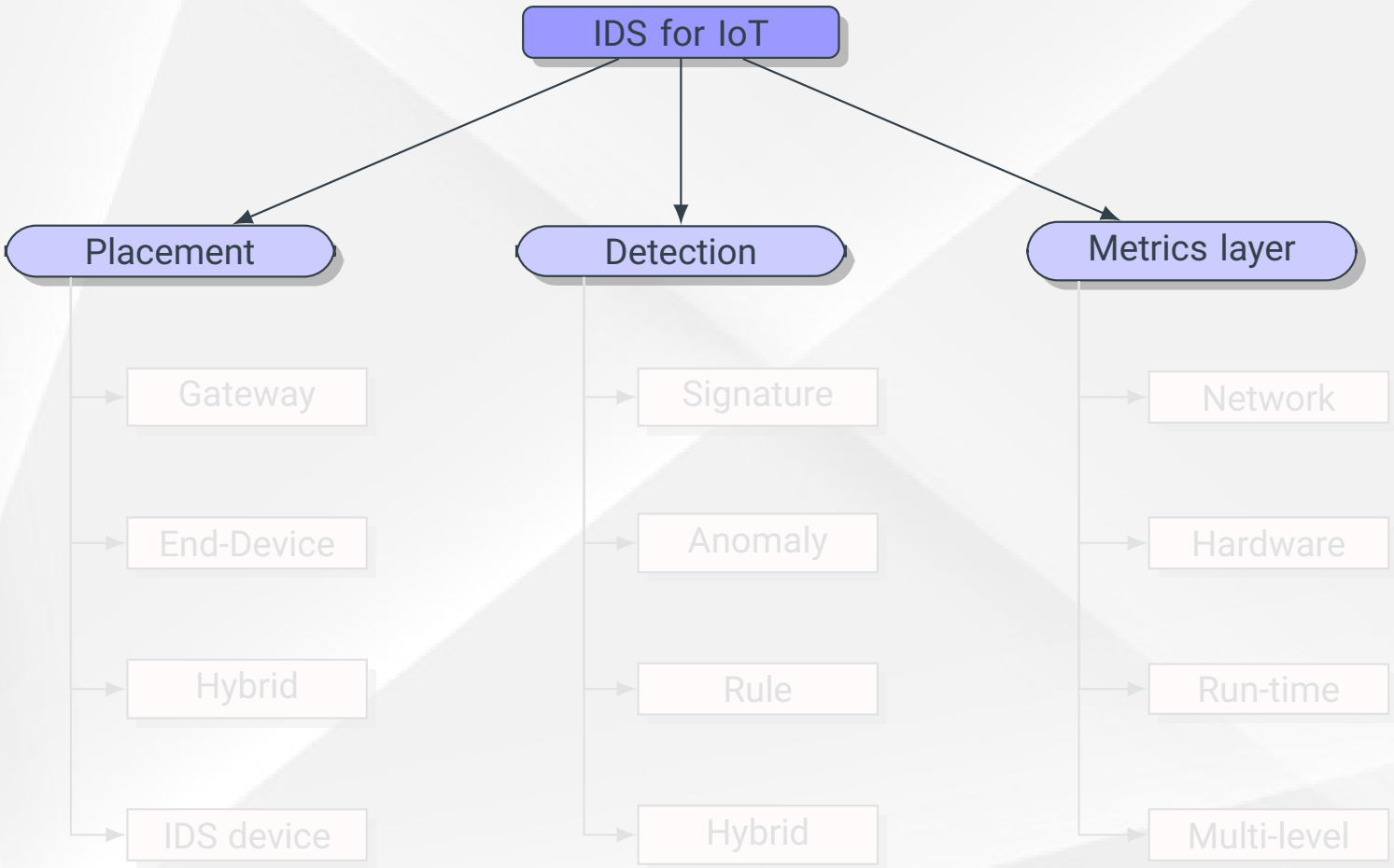

Figure: IDS taxonomy for IoT environment

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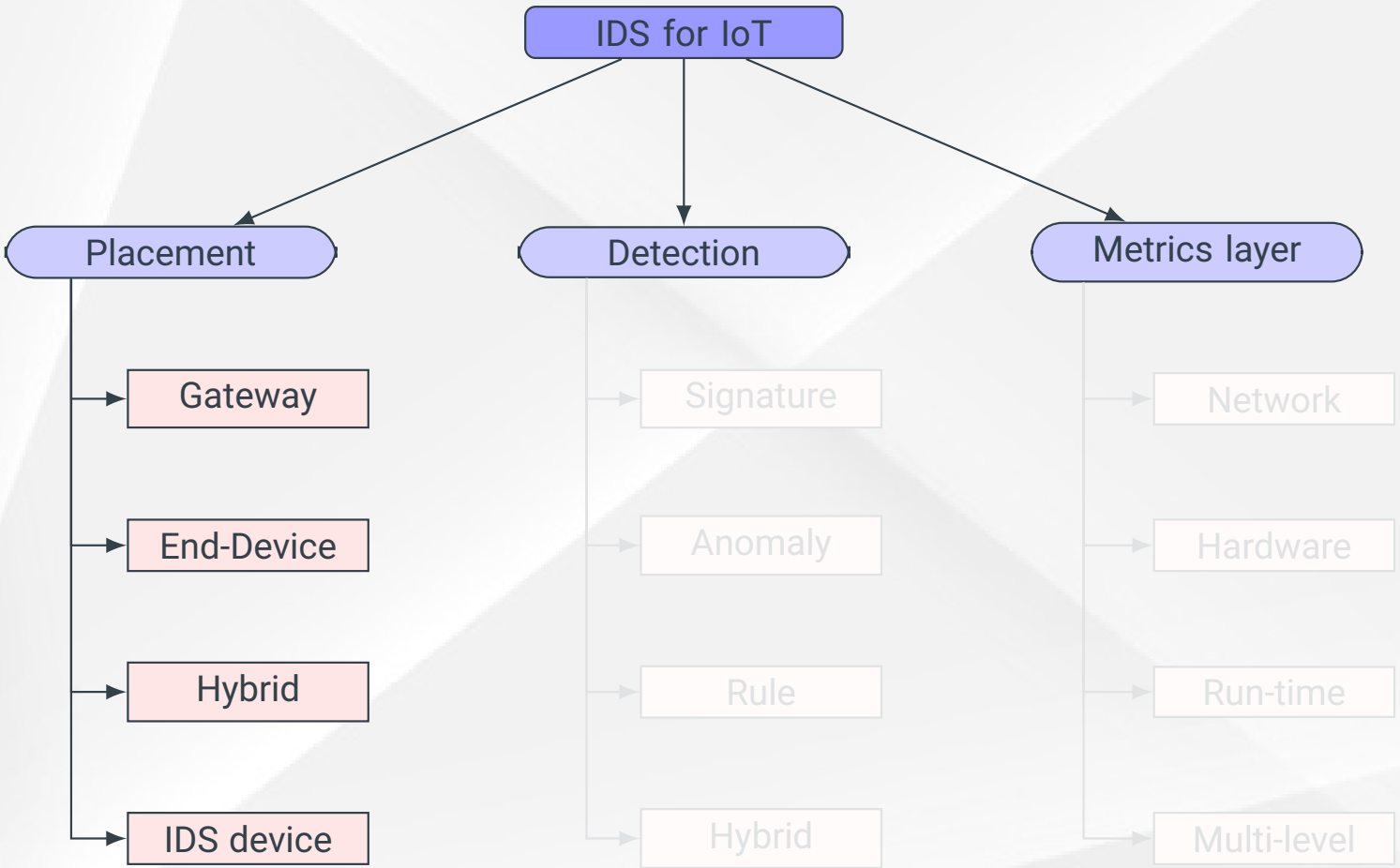

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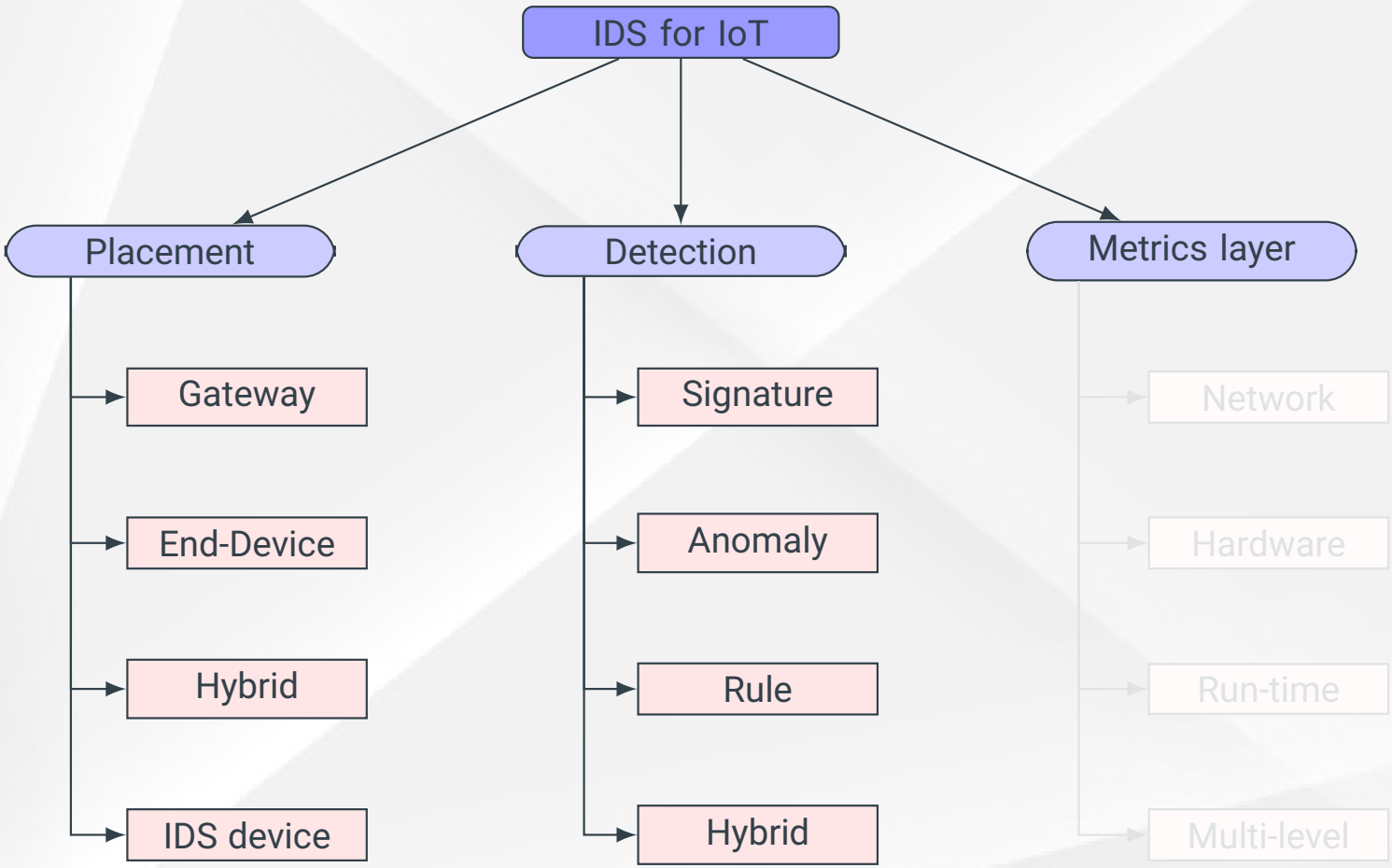

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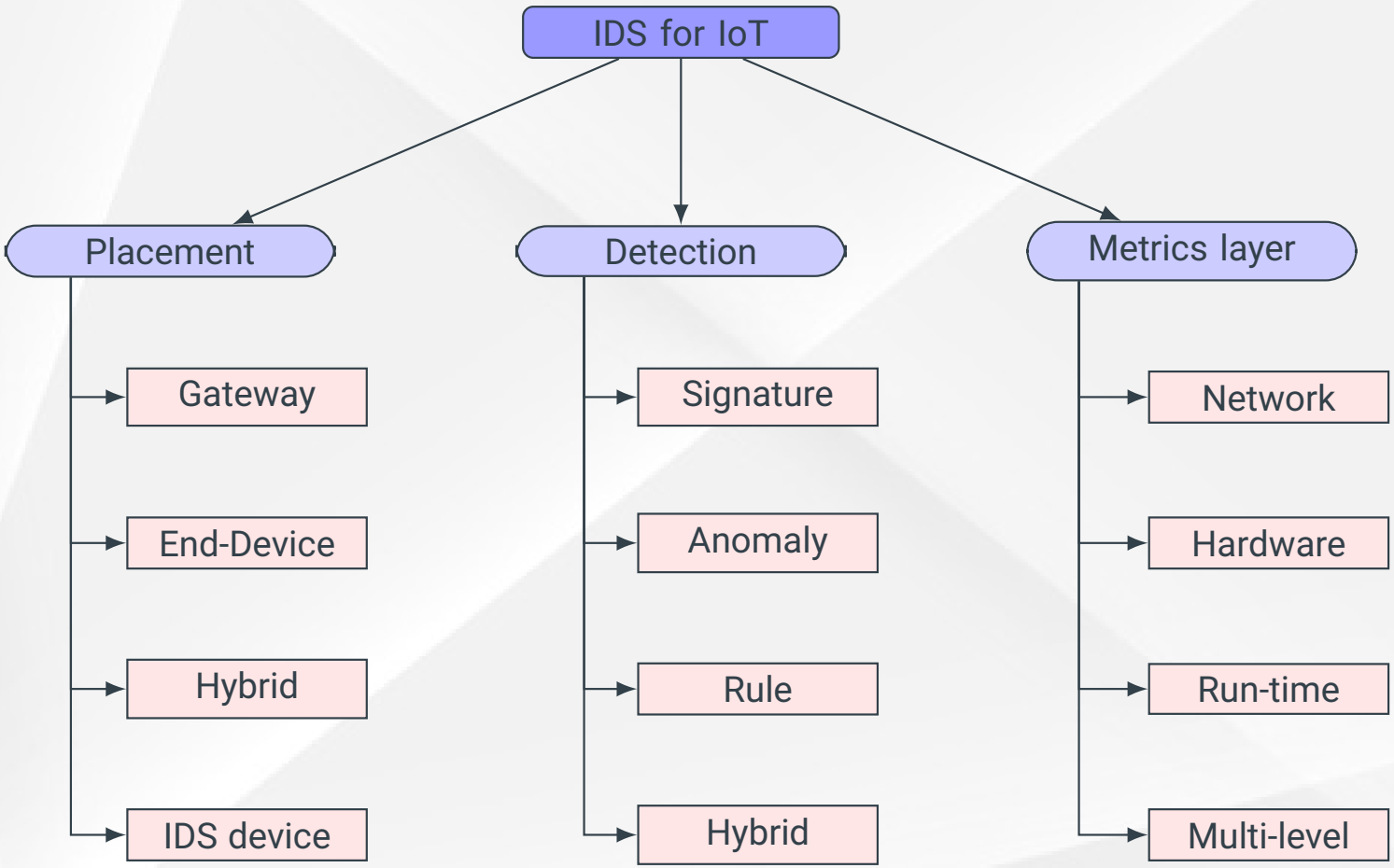

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Host based IDS in state of the art

What are the accurate metrics to record for an HIDS?

Ref	PHY	MAC	UL	μProc	RT	Target	PS	DM	Place
[Yan et al., 2020]	RSSI	-	-	-	-	Spoof	Model legiti.RSSI	B	G / RC
[Zhang et al., 2013]	RSSI	TS	TS	-	-	integrity	SDR	B	D
[Sousa et al., 2017]	-	P	-	-	-	DoS	Analyze & store	S	RC
[Kasinathan et al., 2013]	-	P	-	-	-	DoS, Jamm	SURICATA	S	D
[Eskandari et al., 2020]	Trafic	P	-	-	-	P.inject	GUI LINUX	S	G
[Raza et al., 2013]	-	P	-	-	-	Rout, Snik	IDS + min.FW	B+S	H
[Saeed et al., 2016]	-	-	Sensor	IMA	-	P.inject, DoS	C.Instru + ML	B	G
[Gassais et al., 2020]	-	-	-	CTF	-	DD/DoS	Tracing + ML	S	H
[Bourdon et al., 2021]	-	-	-	HPC	-	P.inject	Tracing + ML	B	H
[Breitenbacher et al., 2019]	-	-	-	-	SC	0-day, DoS	LKM + Whitelist	B	RC

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- **MAC**(Mac layer): **TS**(Time series), **P**(Packet Header)
- **UP**(Upper layers): **TS**(Time series)
- **HW**(Hardware/processor) : **IMA**(Illegal memory access), **HPC**(Hardware Performance counter)
- **SW**(Software/runtime): **SC**(Syscalls)
- **Target attacks**: **Spoof**(Spoofing), **Jamm**(Jamming), **P.inject**(Packet Injection), **Rout**(Rooting), **Snik**(Sinkhole)
- **PS**(Proposed Solution): **LKM**(Loadable kernel module), **min.FW**(mini firewall), **ML**(Machine Learning)
- **DM**(Detection Methodology): **B**(Behavior), **S**(signature)
- **Place**(Placement Strategy): **RC**(Resource constraint), **G**:(Gateway), **D**(Device), **H**(Hybrid)

The multi-level approach is not yet addressed in the state of the art

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The multi-level approach is not yet addressed in the state of the art

Host based IDS in state of the art

What are the accurate metrics to record for an HIDS?

Ref	PHY	MAC	UL	μProc	RT	Target	PS	DM	Place
[Yan et al., 2020]	RSSI	-	-	-	-	Spoof	Model legiti.RSSI	B	G / RC
[Zhang et al., 2013]	RSSI	TS	TS	-	-	integrity	SDR	B	D
[Sousa et al., 2017]	-	P	-	-	-	DoS	Analyze & store	S	RC
[Kasinathan et al., 2013]	-	P	-	-	-	DoS, Jamm	SURICATA	S	D
[Eskandari et al., 2020]	Trafic	P	-	-	-	P.inject	GUI LINUX	S	G
[Raza et al., 2013]	-	P	-	-	-	Rout, Snik	IDS + min.FW	B+S	H
[Saeed et al., 2016]	-	-	Sensor	IMA	-	P.inject, DoS	C.Instru + ML	B	G
[Gassais et al., 2020]	-	-	-	CTF	-	DD/DoS	Tracing + ML	S	H
[Bourdon et al., 2021]	-	-	-	HPC	-	P.inject	Tracing + ML	B	H
[Breitenbacher et al., 2019]	-	-	-	-	SC	0-day, DoS	LKM + Whitelist	B	RC

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[Bourdon et al., 2021]	-	-	-	HPC	-	P.inject	Tracing + ML	B	H
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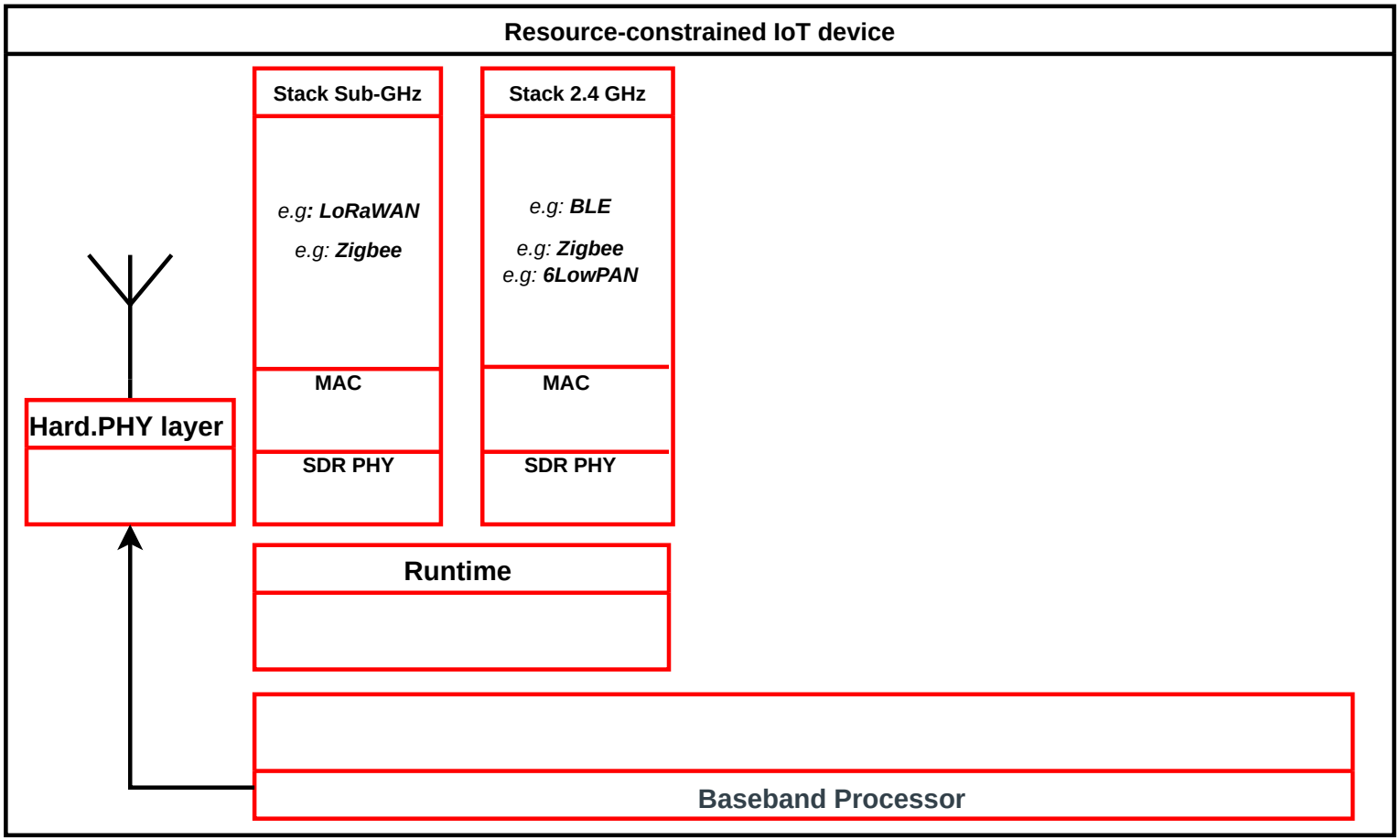
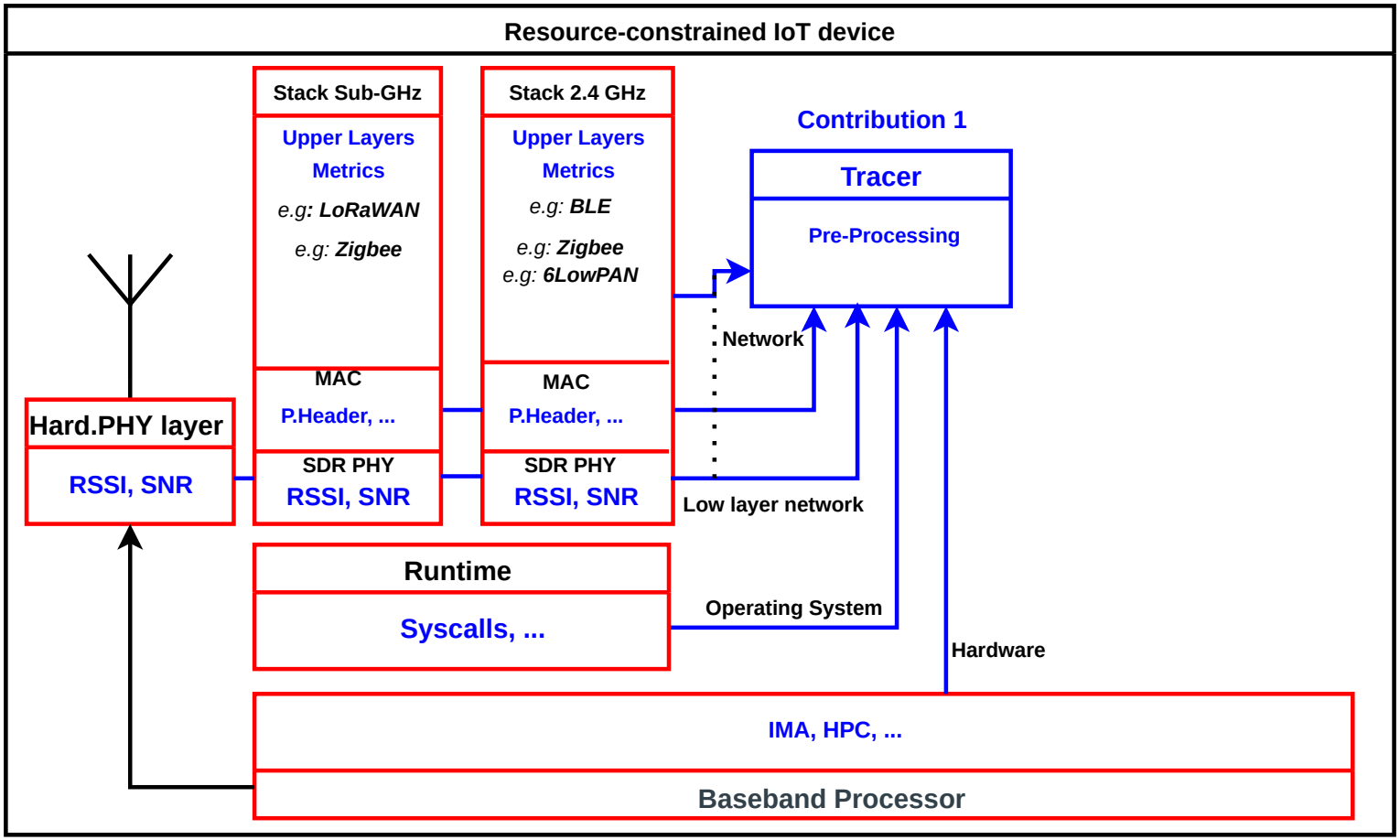
Towards a multi-level metrics HIDS



Wireless connectivity block diagram with IDS

Towards a multi-level metrics HIDS



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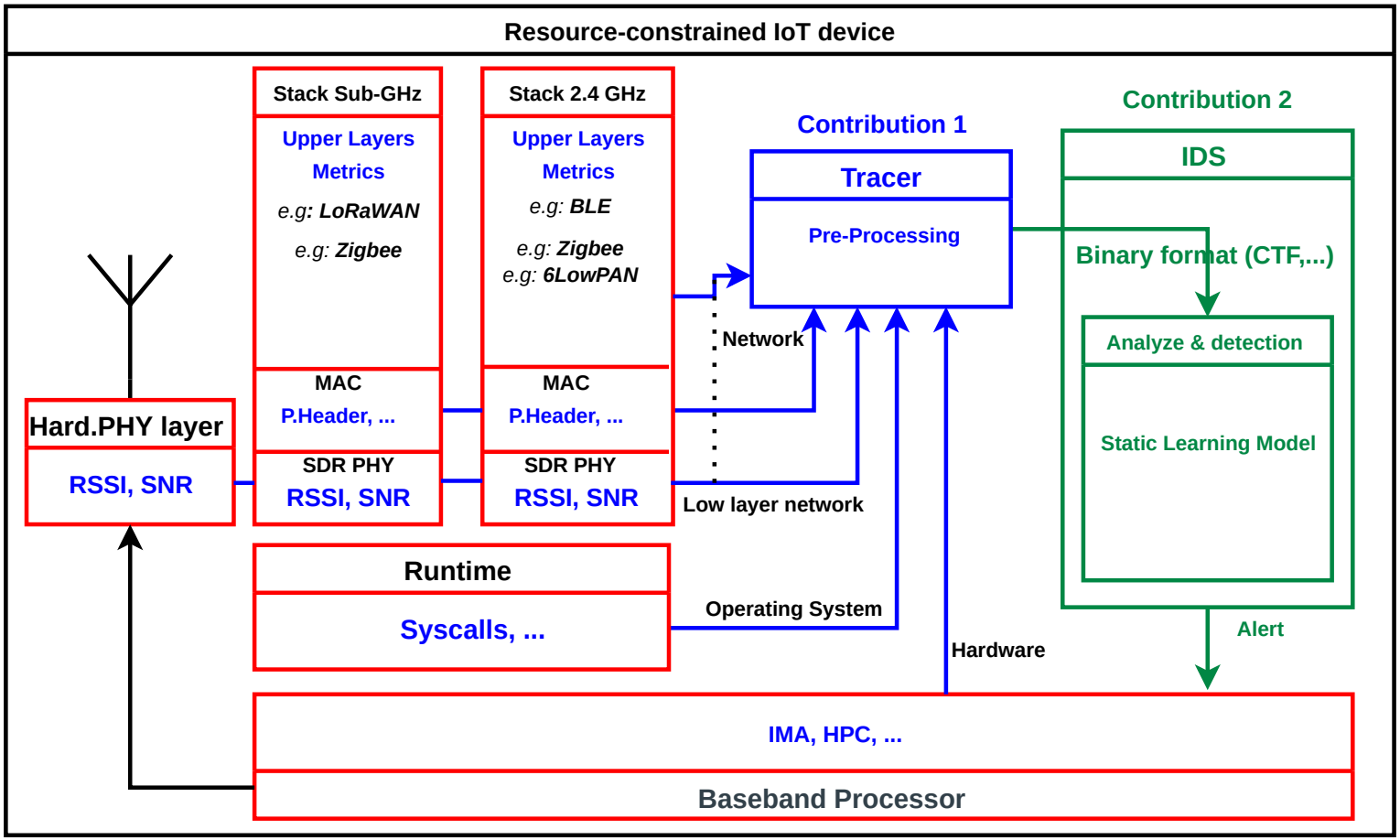
Towards a multi-level metrics HIDS



Wireless connectivity block diagram with IDS

Outline

1. Threat model and countermeasures
2. Proposed security mechanism: a multi-metrics HIDS
3. **Test-bed & Evaluation**
   - Objective
   - Test-bed
   - Preliminary results
   - Conclusion

Objective

- **Proposed Hardware :**
  - CV32E41P RISC-V Processor for handling the wireless connectivity
  - Record Hardware Performance Counters (HPC) from CV32E41P by HPMtracer (Hardware block)

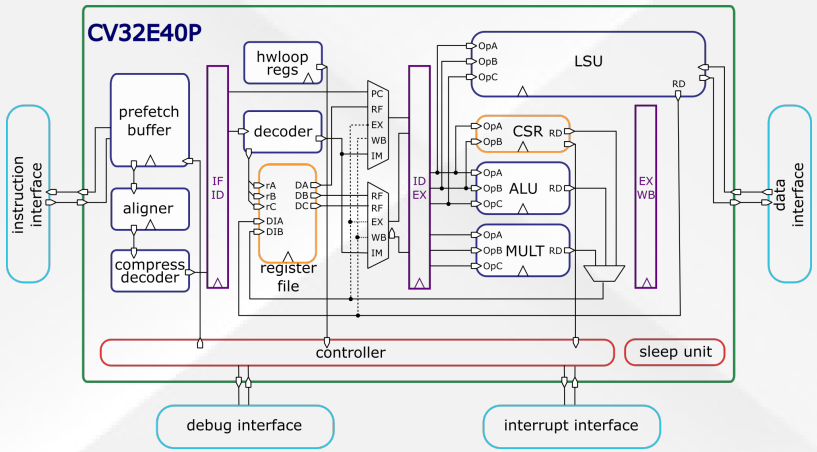


Figure: CV32E41P/40P block diagram

- **Scenario**
  - Reproduction of simple buffer overflow exploit on software running on wireless connectivity area
  - Build a dataset of HPC values per each packet network

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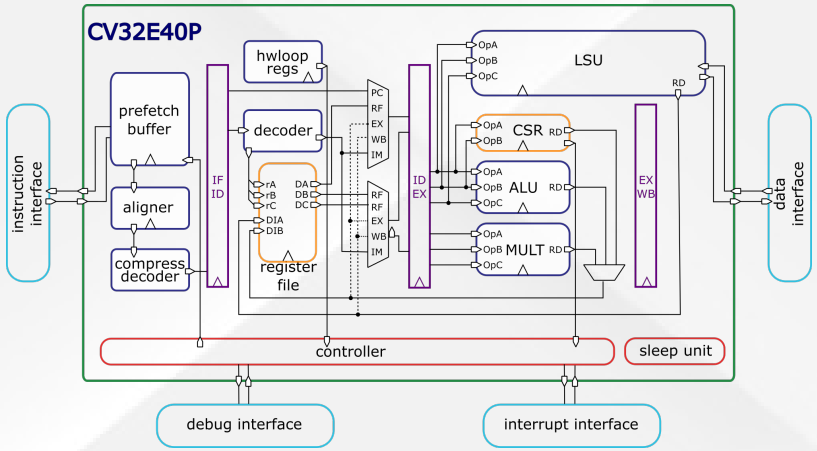

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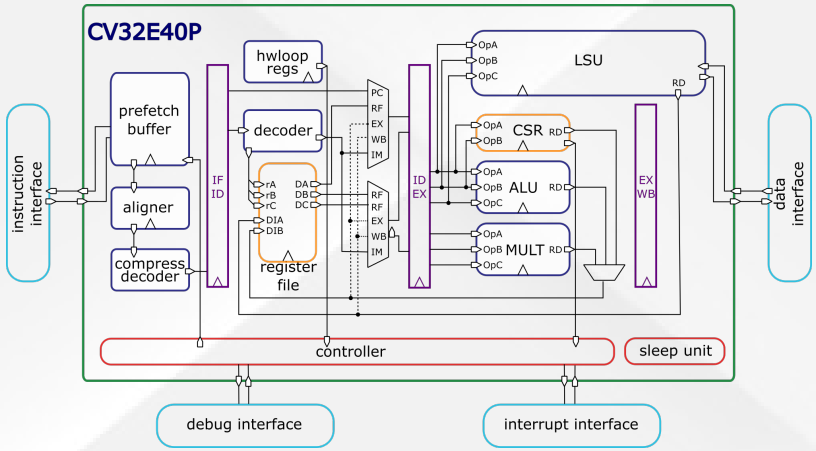

Figure: CV32E41P/40P block diagram

- **Scenario**
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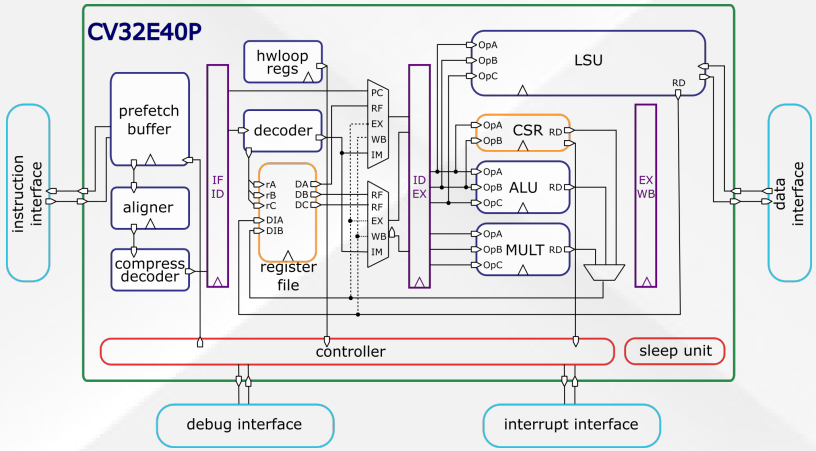

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Test-bed with tracing metrics from RISC-V CV32E41P

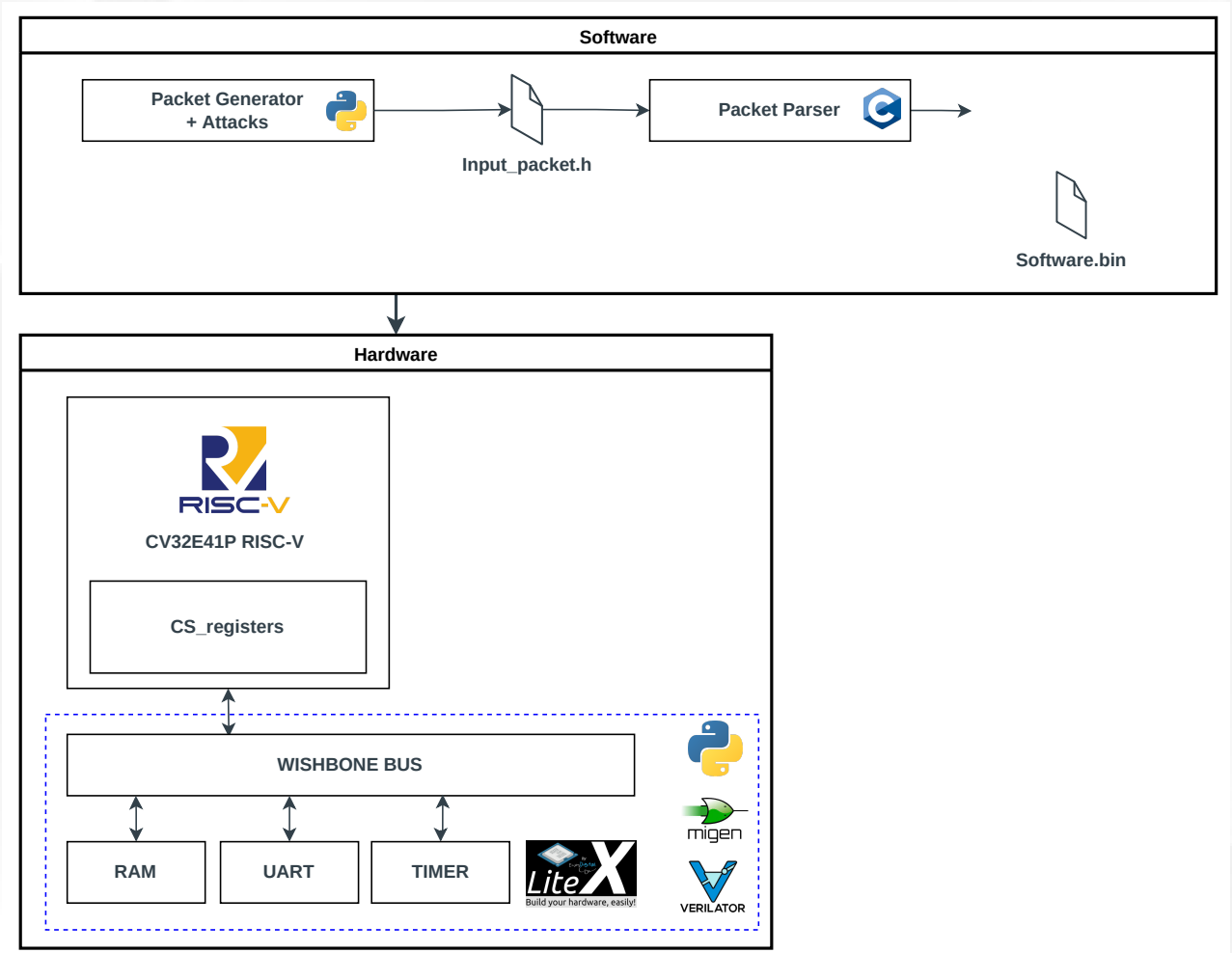
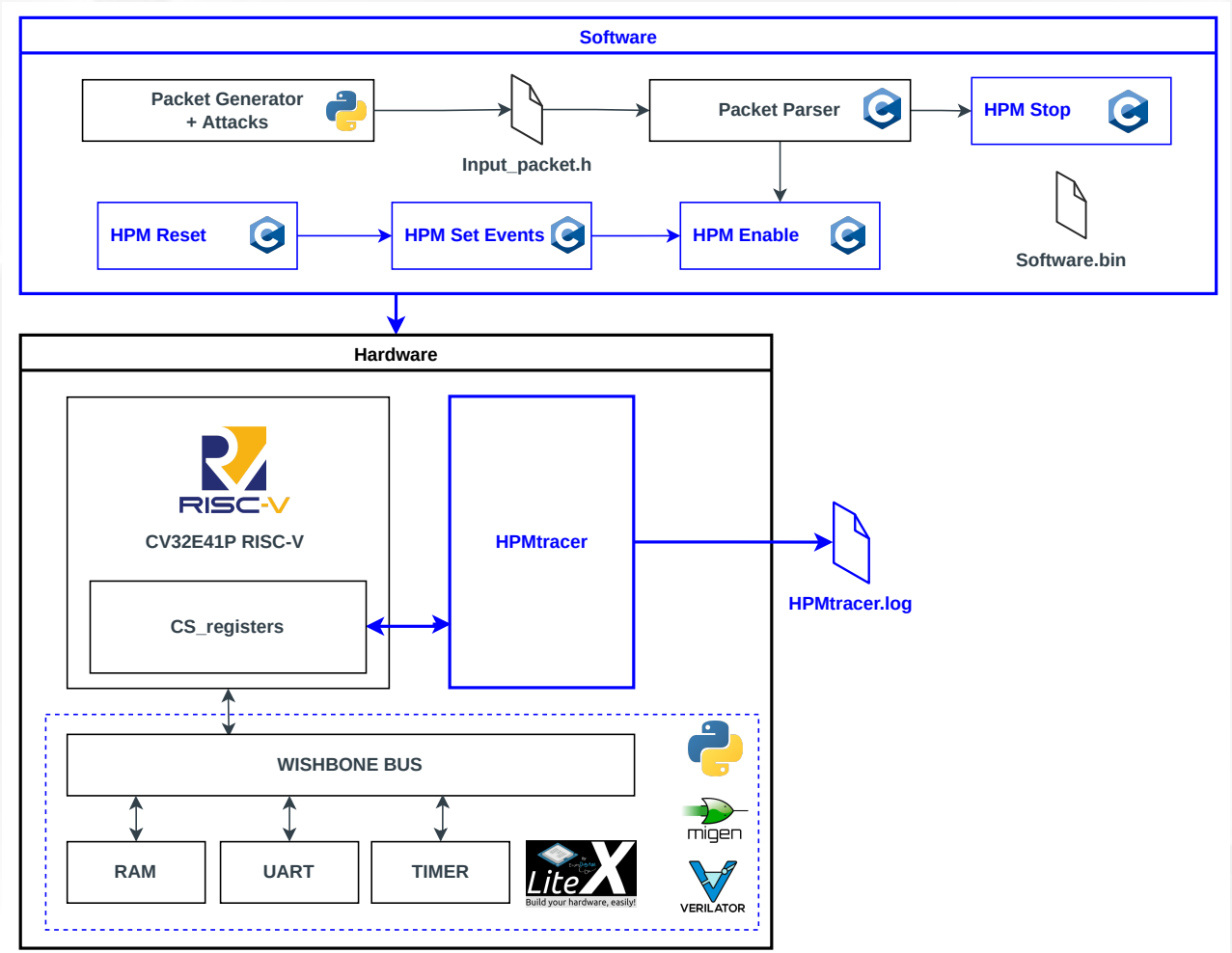


Figure: Test-bed block diagram

Test-bed with tracing metrics from RISC-V CV32E41P



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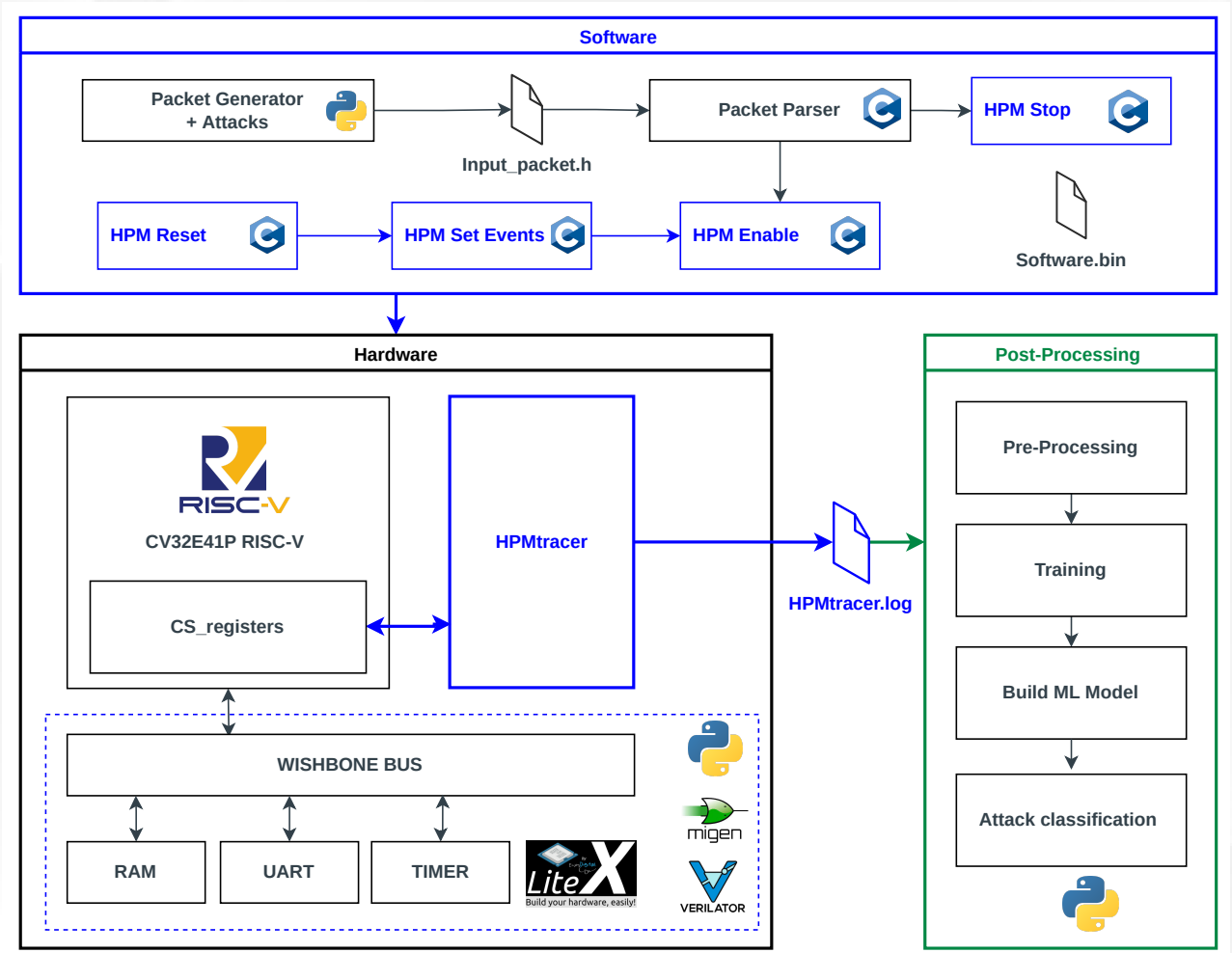

Figure: Test-bed block diagram

Dataset

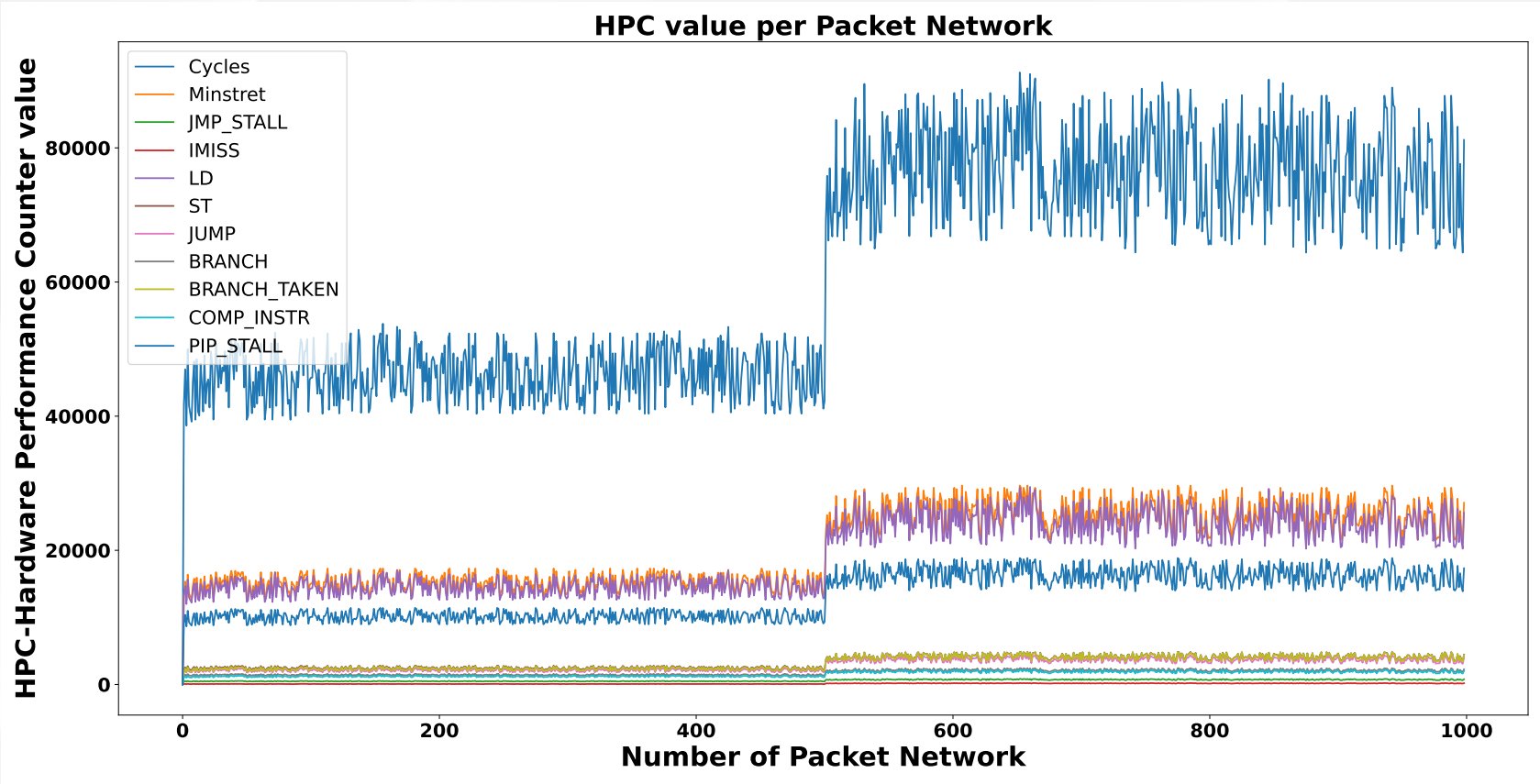

Figure: Dataset from HPC monitors

Preliminary results

This table shows the evaluation results of the comparison of several classification algorithms.

Method	Accuracy	Precision	Recall	F1 score
Nearest Neighbors	0.998	0.995	1.00	0.998
Linear SVM	0.998	0.995	1.00	0.998
RBF SVM	0.765	1.000	0.550	0.710
Gaussian Process	0.887	1.000	0.785	0.879
Decision Tree	0.998	0.995	1.000	0.998
Random Forest	0.998	0.995	1.000	0.998
Neural Net	0.583	0.977	0.206	0.340
AdaBoost	0.998	0.995	1.000	0.998
Naive Bayes	0.995	0.995	0.995	0.995
QDA	0.995	0.995	0.995	0.995

- Interesting Results
- An in-depth study to follow

Conclusion

- **Ongoing work**
  - New approach for monitoring and detecting software attacks from a network entry point.
  - Test-bed to detect buffer overflow using hardware counters.
  - Promising results of machine learning classification algorithms.
- **Future work**
  - Tracer Implementation.
  - Lightweight IDS Detection Module on Co-processor.
  - Tracer & IDS Evaluation (Detection, Benchmarks, Overhead, Power consumption).

THANK YOU

Towards Low-Power and Low Data-Rate Software-Defined Radio Baseband with RISC-V Processor for Flexibility and Security

18th CryptArchi Workshop - Porquerolles 2022

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Lab-STICC, Team ARCAD, Université Bretagne Sud, Lorient, France

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