Industry 4.0: Industrial IoT Enhancement and WSN Performance Analysis

Doctoral Program in Control and Computer Engineering (33.th cycle)

Torino, 2021/09/16

Candidate:

Mohammad Ghazi Vakili

Supervisor:

Prof. Claudio Giovanni Demartini

Committee

Prof. Paulo Portugal, Referee, University of Porto (PT)

Prof. Davide Quaglia, Referee, University of Verona (IT)

Dr. Luca Durante, Senior Researcher at CNR-IEIIT (IT)

Prof. Bartolomeo Montrucchio, Politecnico di Torino (IT)

Prof. Lucia Lo Bello, University of Catania (IT)

Politecnico di Torino

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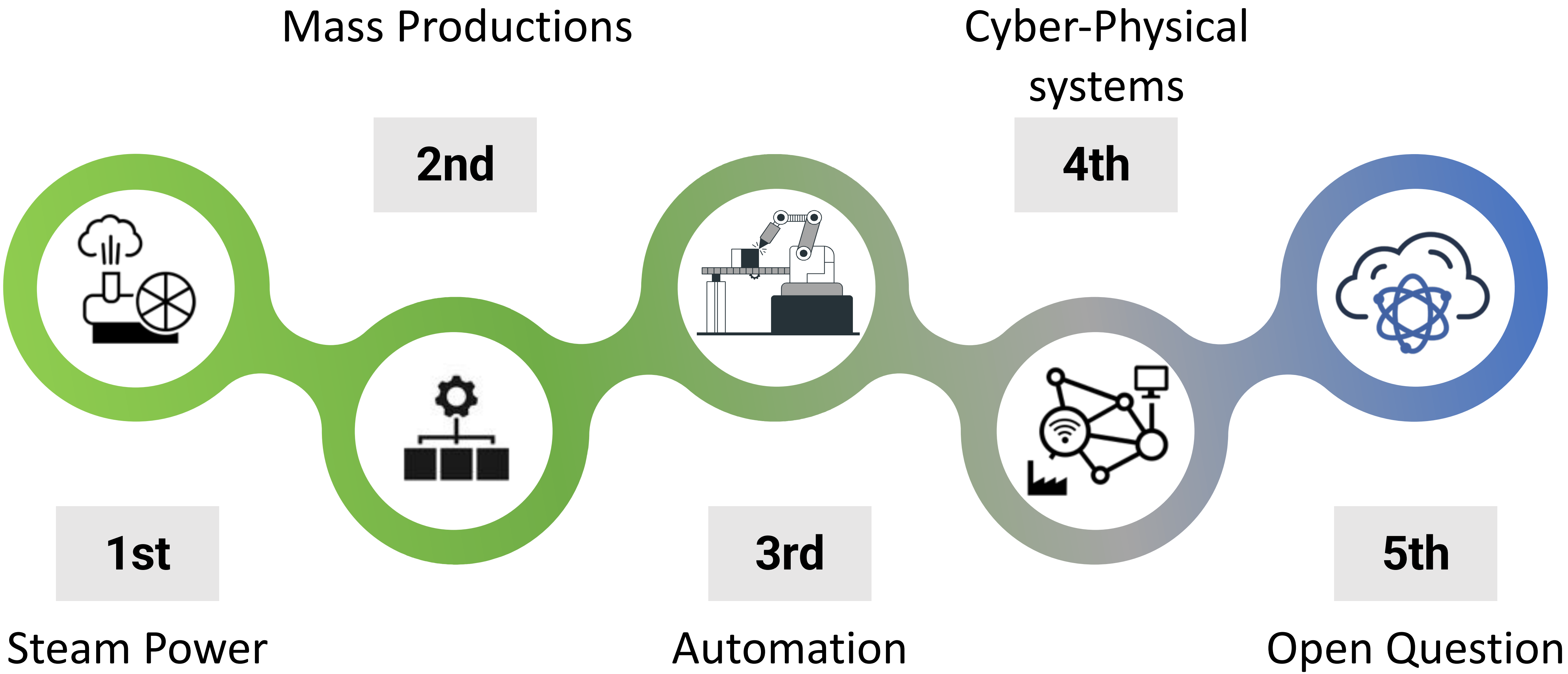
ScuDo

Scuola di Dottorato - Doctoral School

WHAT YOU ARE, TAKES YOU FAR

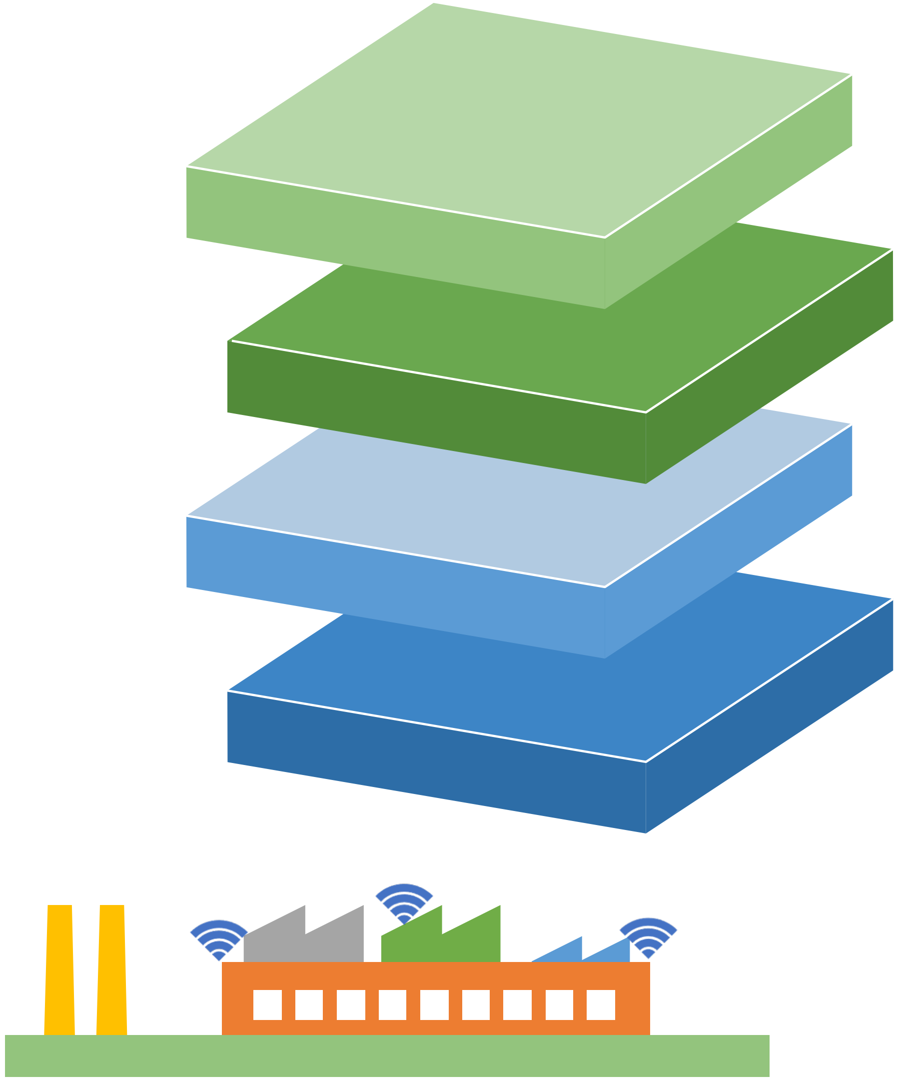
Premise

Industrial Revolutions



Agenda

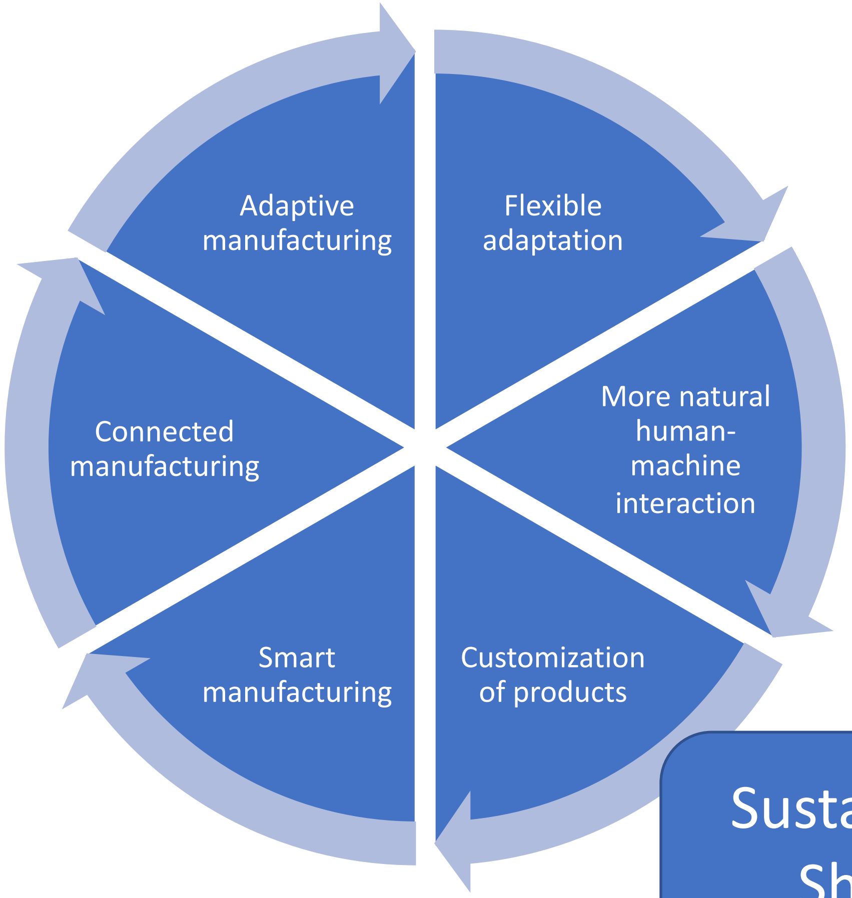
Outline



1. Motivation
2. Challenges & Proposed solutions
3. OPC-IoT Platform
4. IFog4.0
5. TSCH WSN Model
6. TSCH predictor
7. Conclusions &. Future work

Motivation

Problem Statement

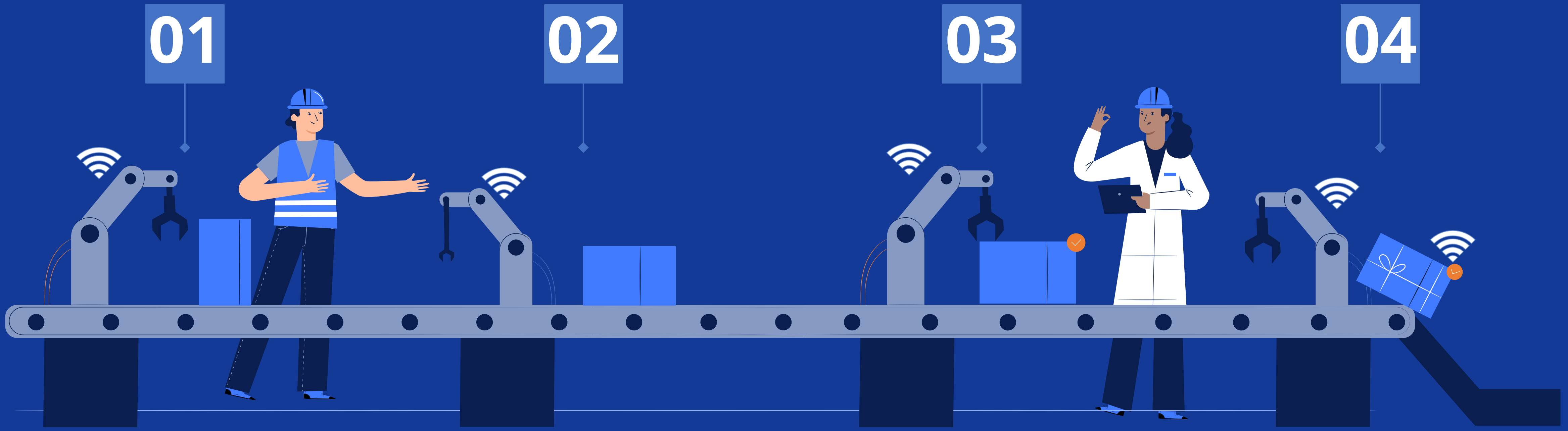


Sustainable communication intra, inter Shopfloor & Business devices and applications

Motivation

Sustainable Communication

High reliability | Low Latency | Low Power | Flexibility



Motivation

- Industry 4.0 challenges
  - Communication challenges
    - IoT standardization
    - WSN Modeling

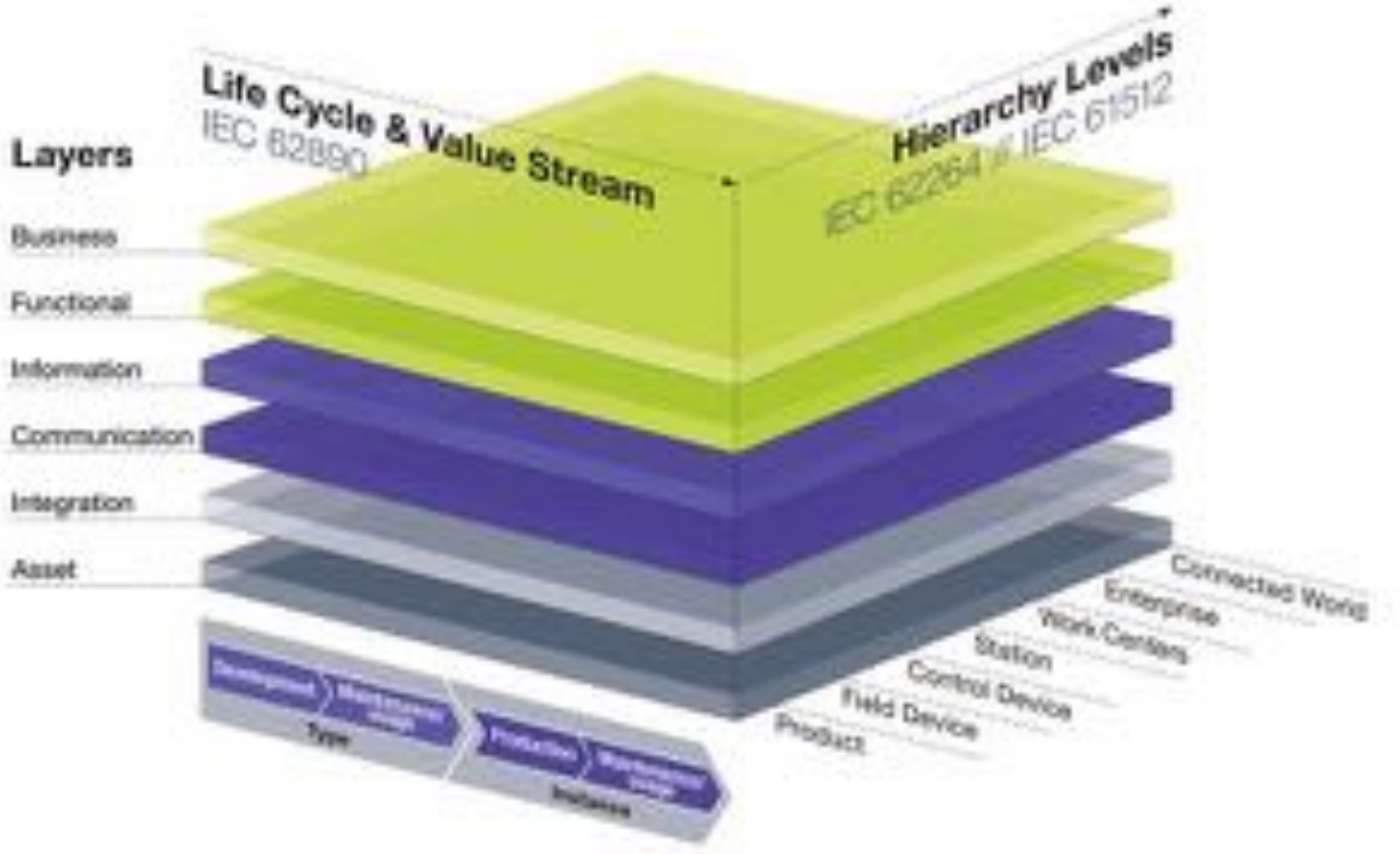
Prerequisites in Industry 4.0 communication

- Defining communication structures
- Development of a common language with its own signs, alphabet, vocabulary, syntax, grammar, semantics, pragmatics and culture

The Road map: RAMI 4.0 – The Reference Architectural Model for Industrie 4.0

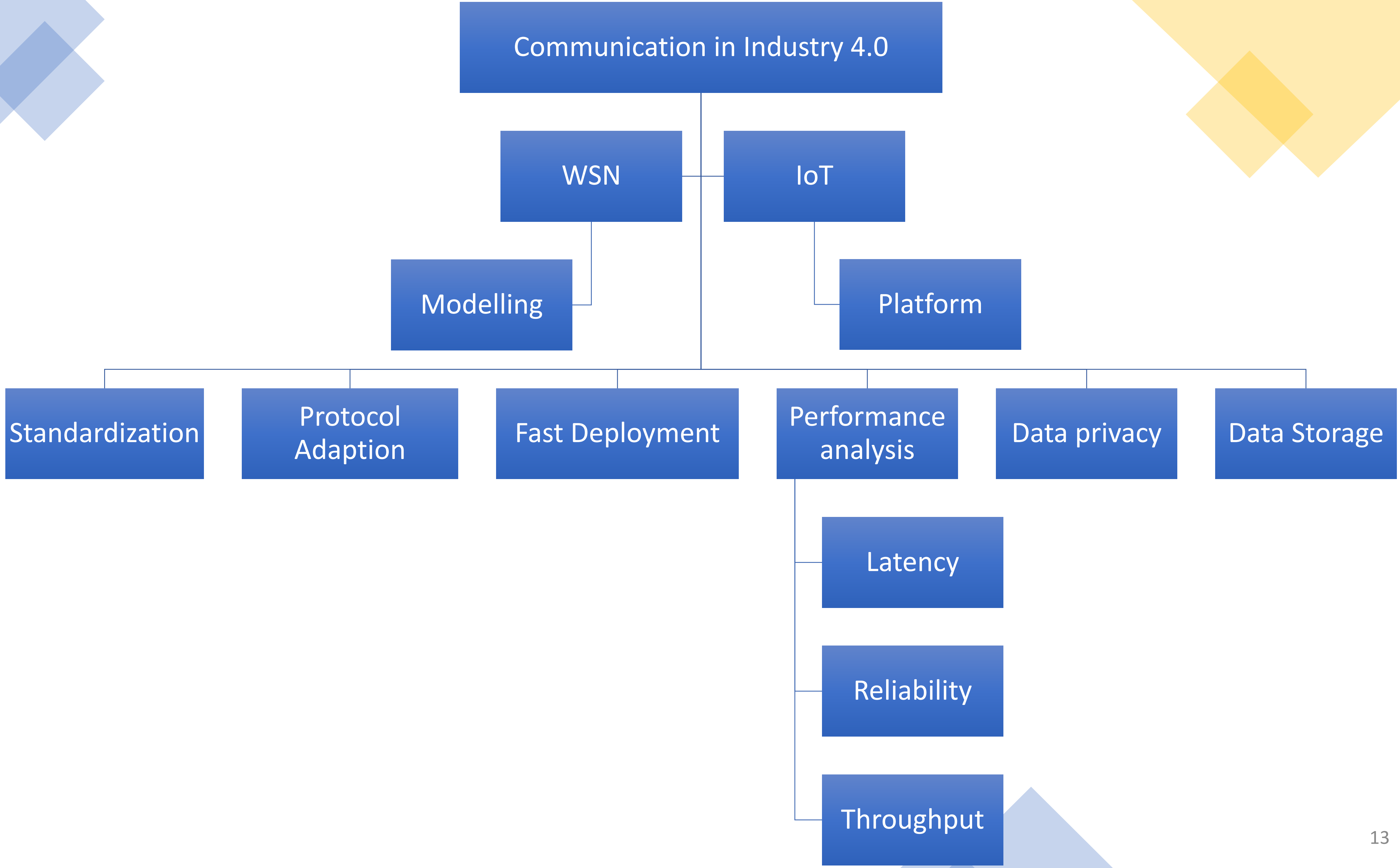
What is RAMI4.0?

- RAMI 4.0 is a three-dimensional map showing how to approach the issue of Industrie 4.0 in a structured manner.
- RAMI 4.0 ensures that all participants involved in Industrie 4.0 discussions understand each other.
- RAMI 4.0 is a SERVICE-ORIENTED ARCHITECTURE.
- RAMI 4.0 combines all elements and IT components in a layer and life cycle model.
- RAMI 4.0 breaks down complex processes into easy-to-grasp packages, including data privacy and IT security.



Challenges

Challenges


Communication in Industry 4.0
WSN
IoT
Modelling
Platform
Standardization
Protocol Adaption
Fast Deployment
Performance analysis
Data privacy
Data Storage
Latency
Reliability
Throughput

Proposed solutions

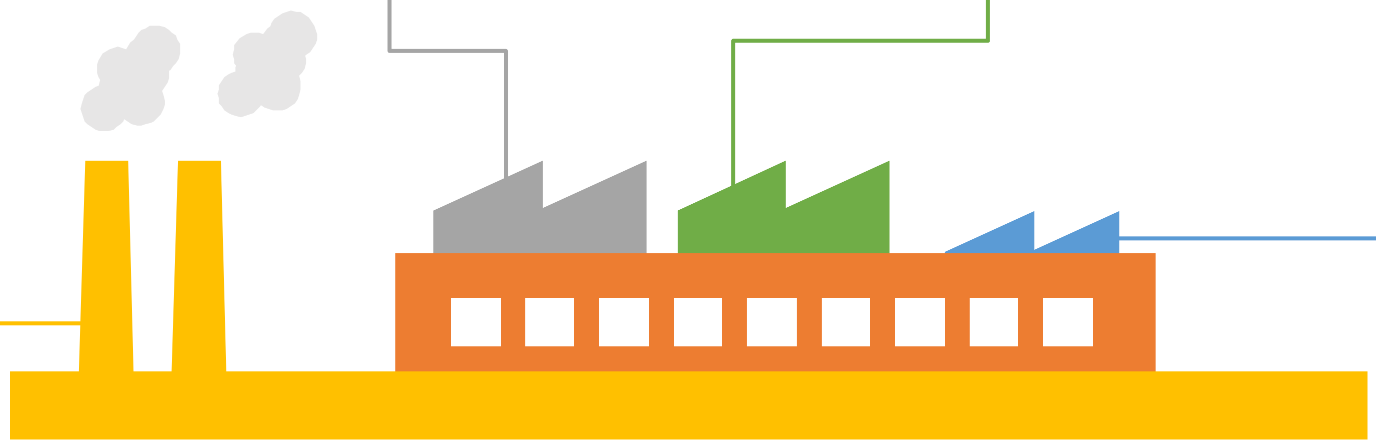
Solutions for Industry 4.0 communication issues

OPC-IoT platform
IoT adoption
Standardization
Performance analysis

IFog4.0
Fast Deployments
Data privacy
Low Latency

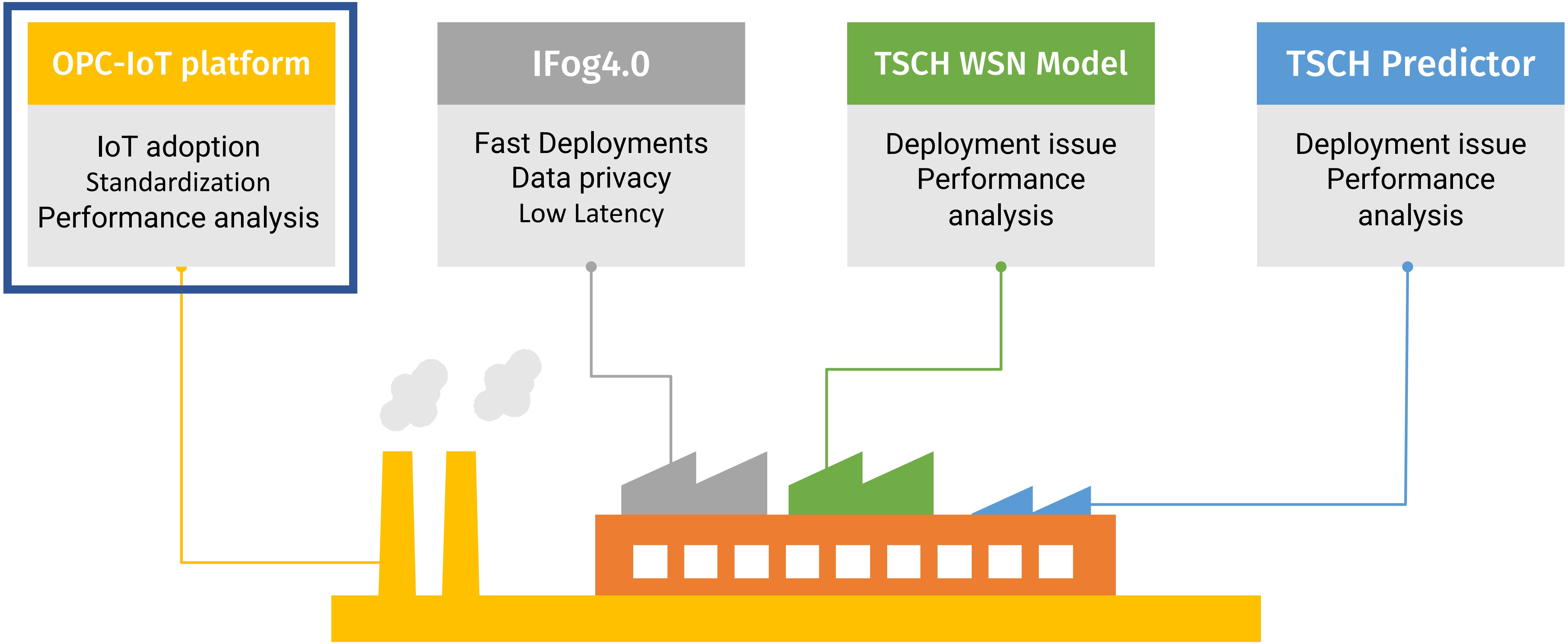
TSCH WSN Model
Deployment issue
Performance analysis

TSCH Predictor
Deployment issue
Performance analysis



OPC-IoT platform

Solutions for Industry 4.0 communication issues



OPC-IoT Platform

IoT challenges

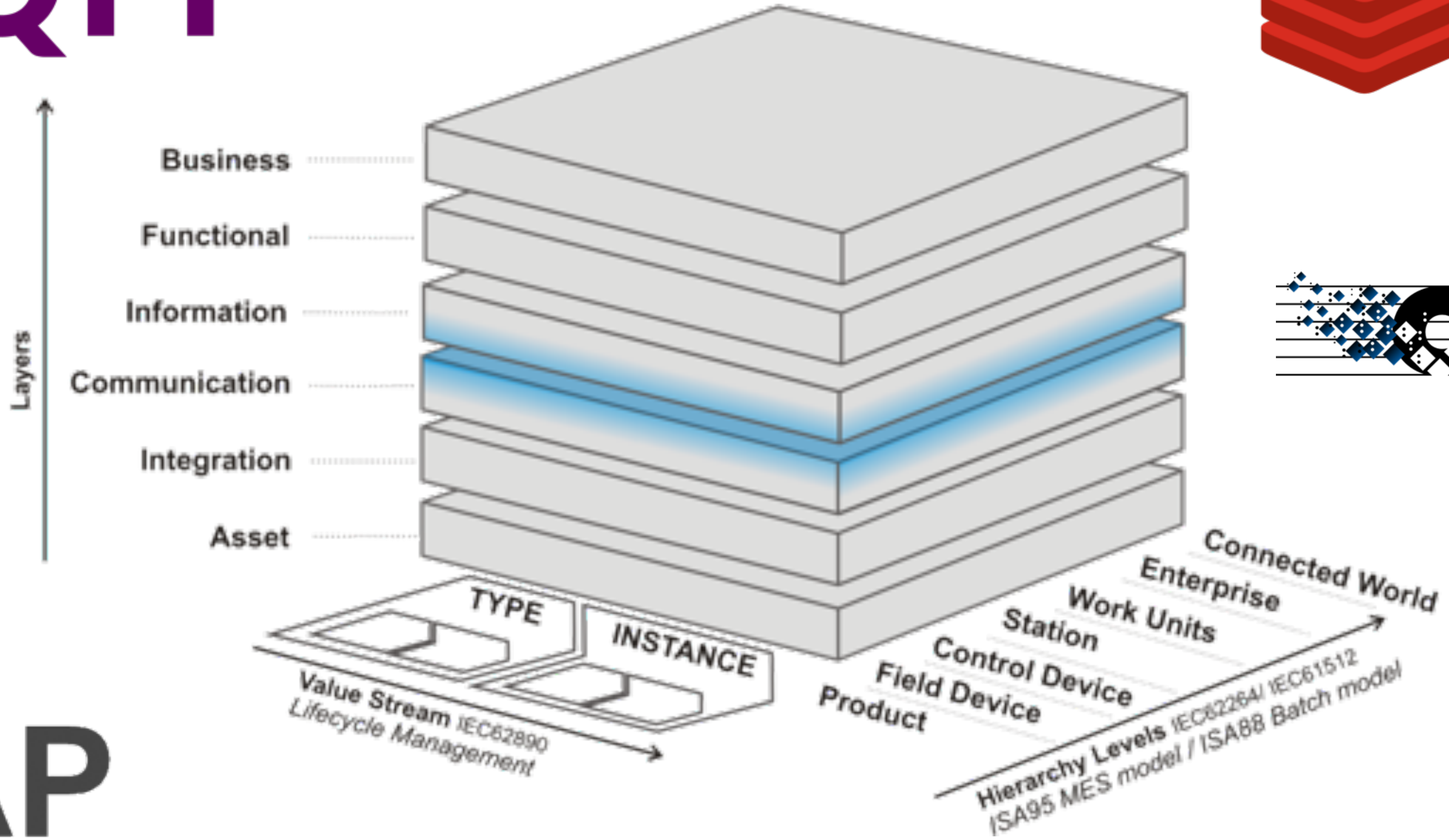
OPC-IoT platform

Industrial IoT Platform Based on RAMI 4.0

MQTT

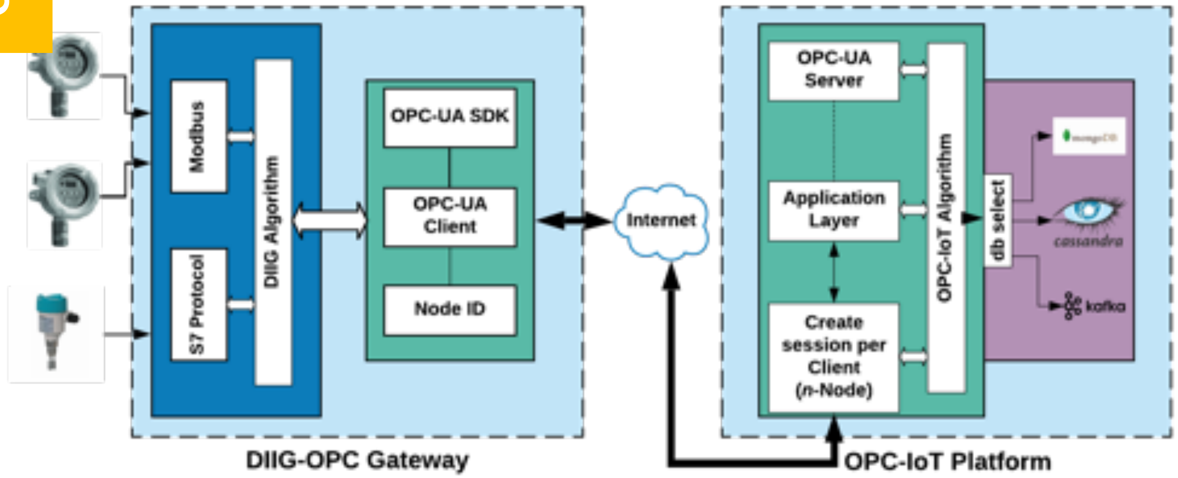
redis

OPC UA

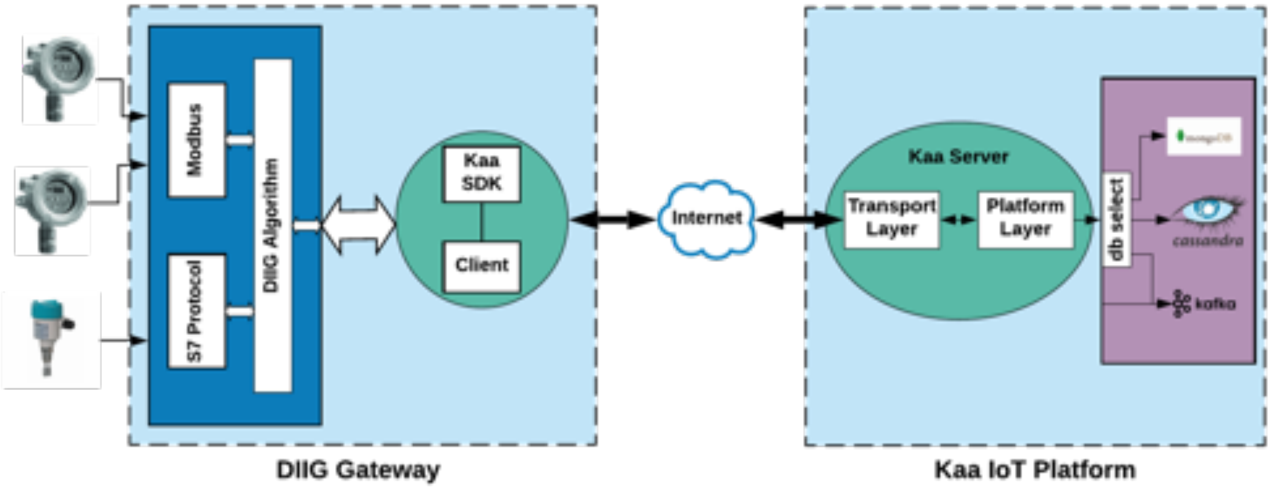


CoAP

Industrial IoT Platform Based on RAMI 4.0

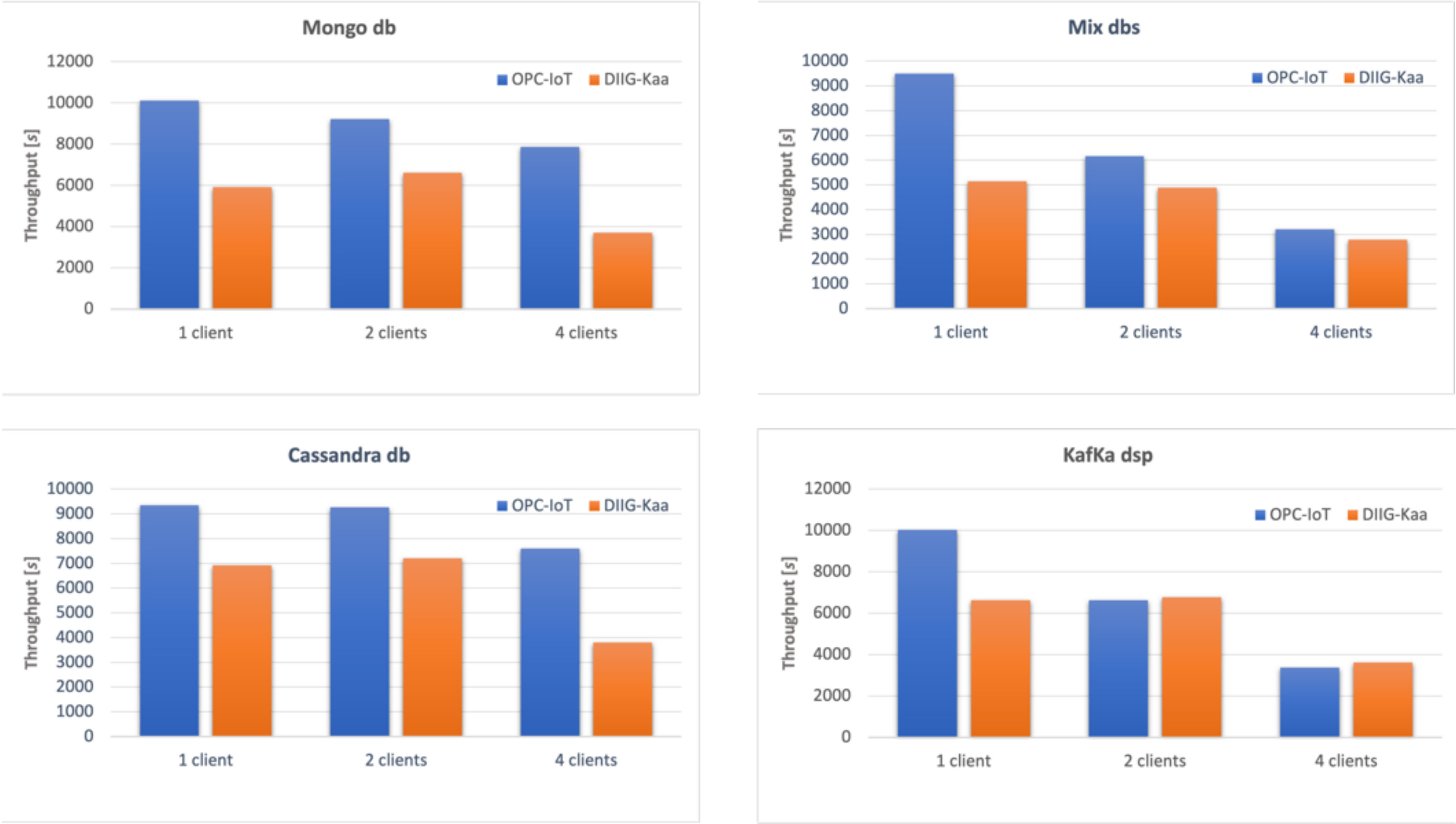


DIIG-OPC architecture components with the IoT platform



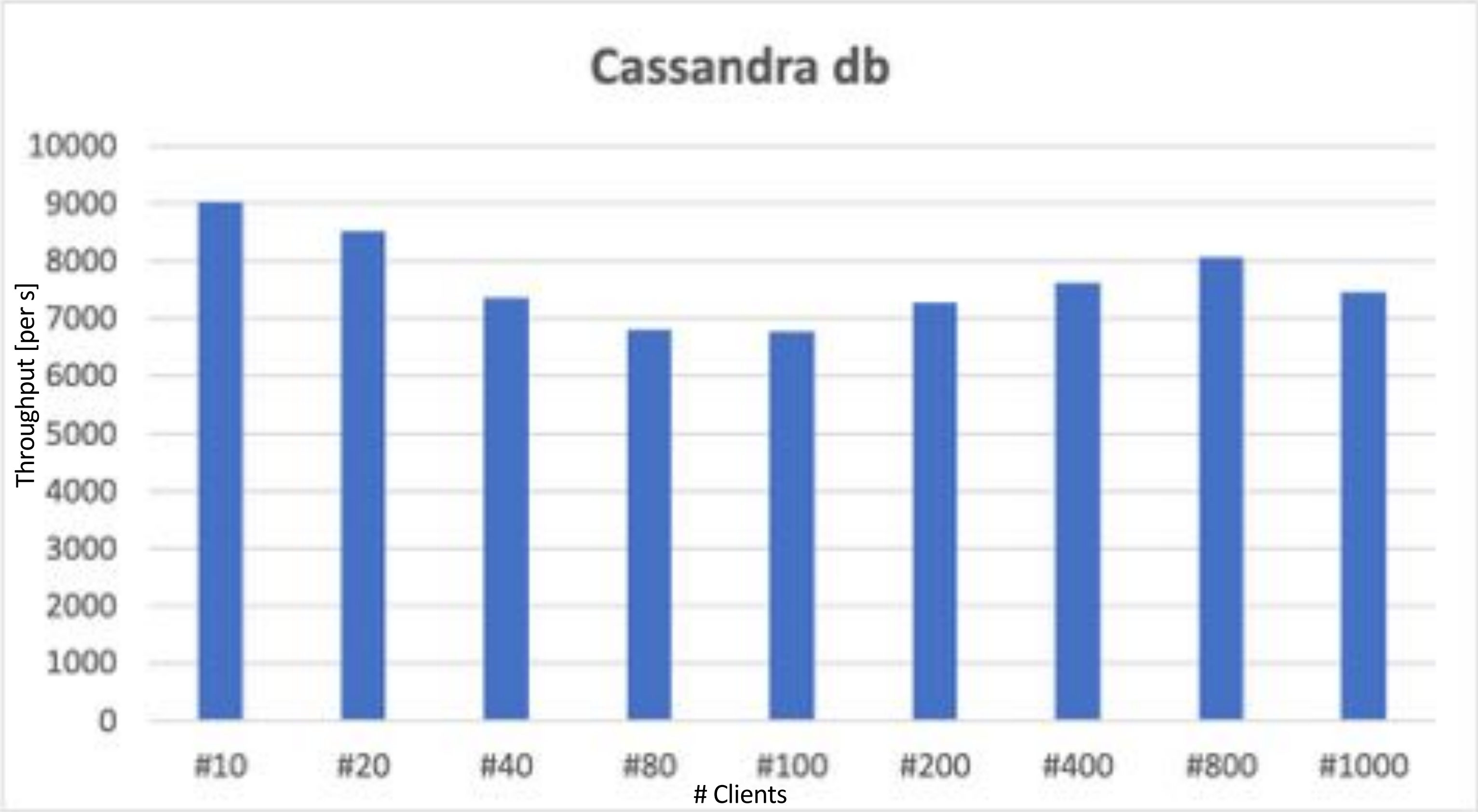
DIIG-Kaa architecture components with Kaa IoT platform

Performance evaluation: Throughput



Result of 100,000 messages that were sent to the server from each client, and the data were stored in various database technologies

Performance evaluation with 1000 clients

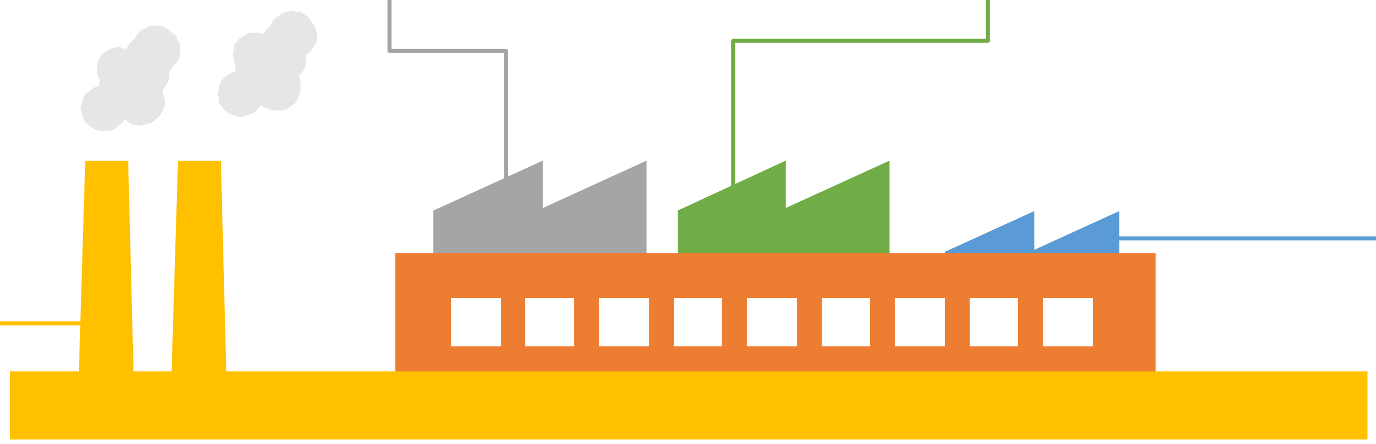


OPC-IoT platform

IoT adoption
Standardization
Performance analysis

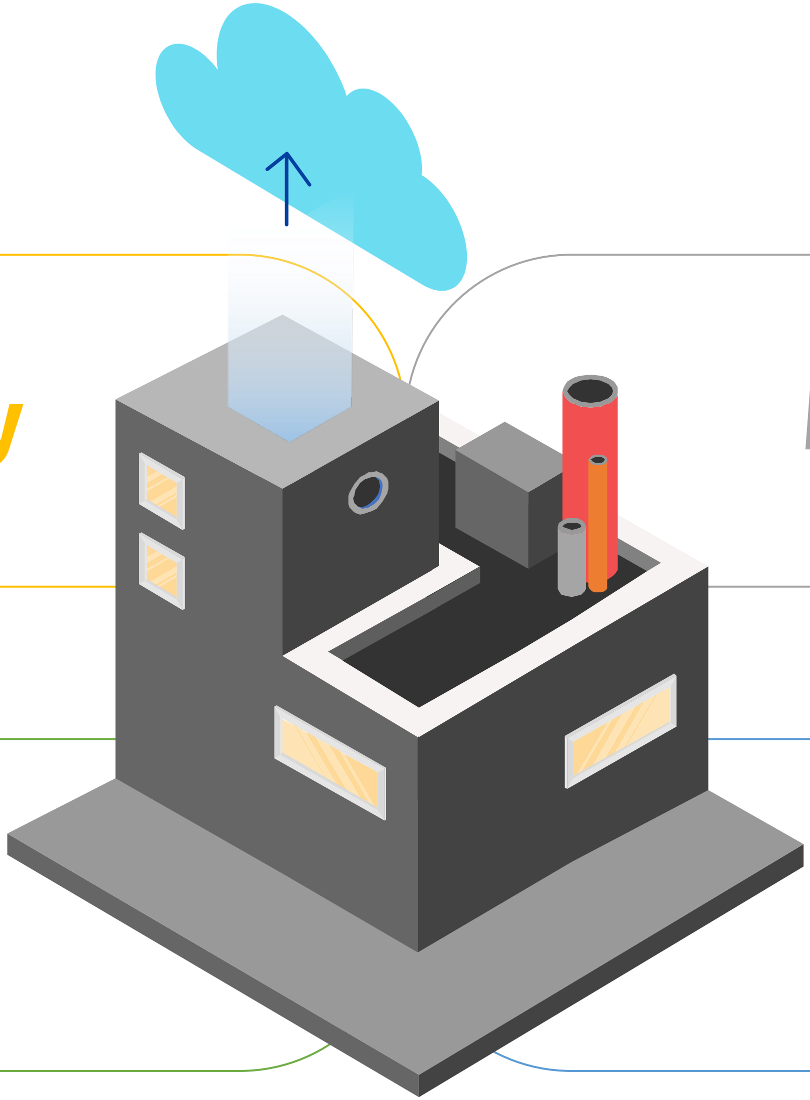
Solutions for Industry 4.0 communication issues

OPC-IoT platform	IFog4.0	TSCH WSN Model	TSCH Predictor
IoT adoption Standardization Performance analysis	Fast Deployments Data privacy Low Latency	Deployment issue Performance analysis	Deployment issue Performance analysis



IFog4.0

IoT Centralization issues

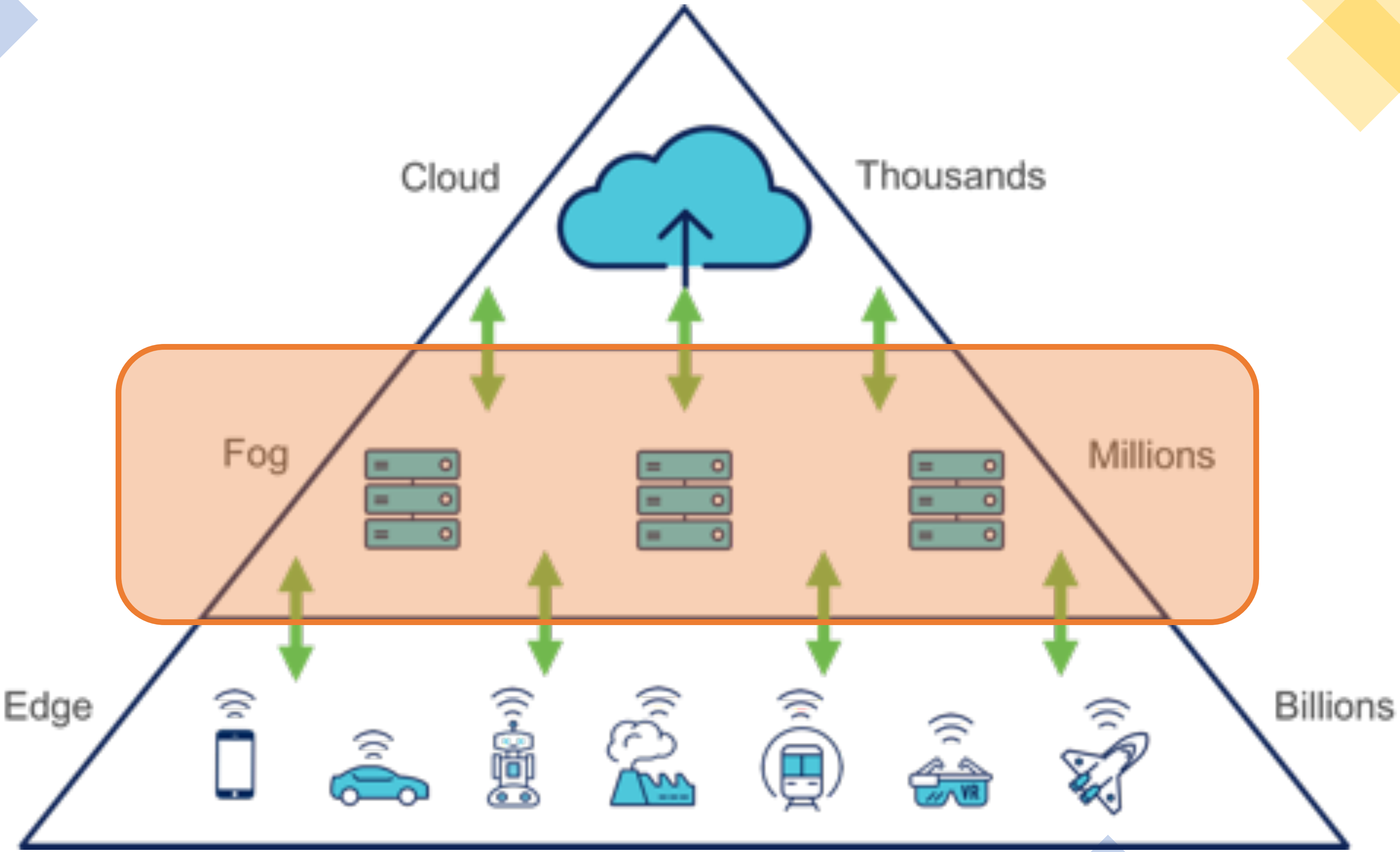


Data privacy

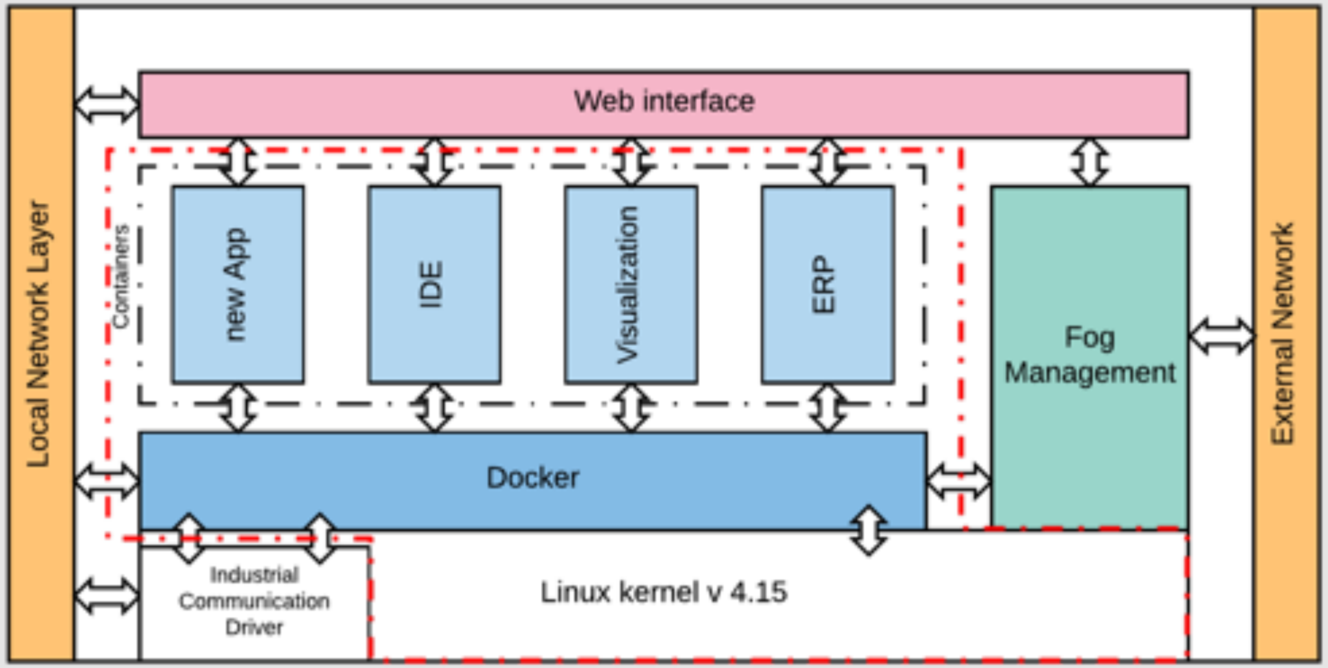
Maintenance

Latency

Deployments

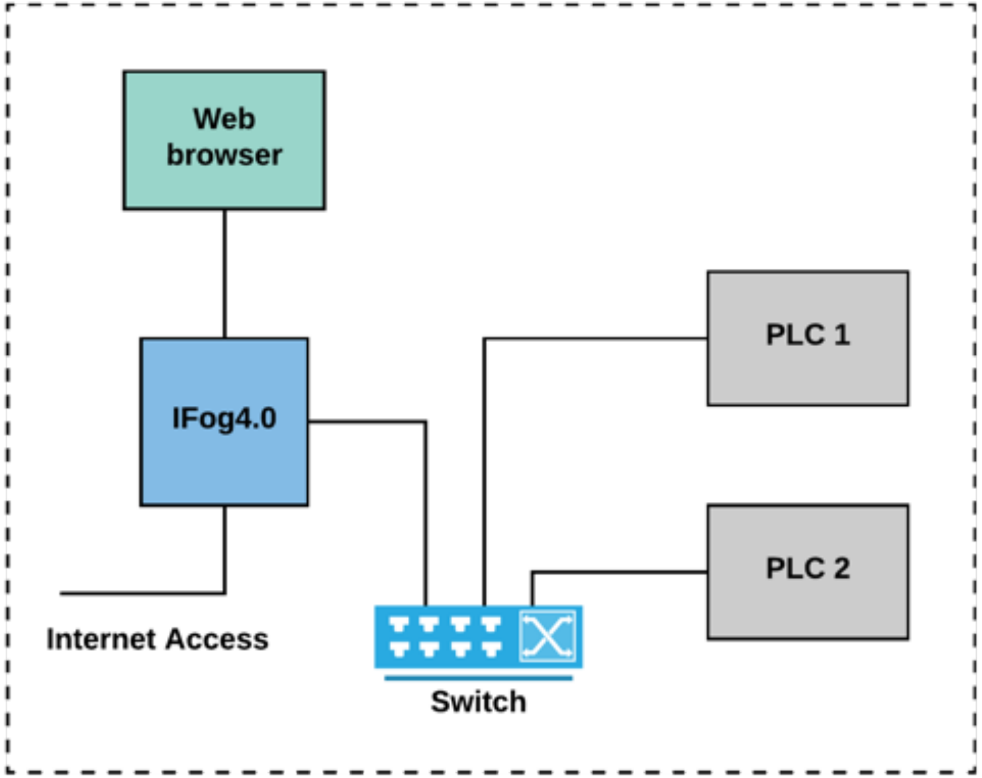

Cloud
Thousands
Fog
Millions
Edge
Billions
VR

Proposed solution

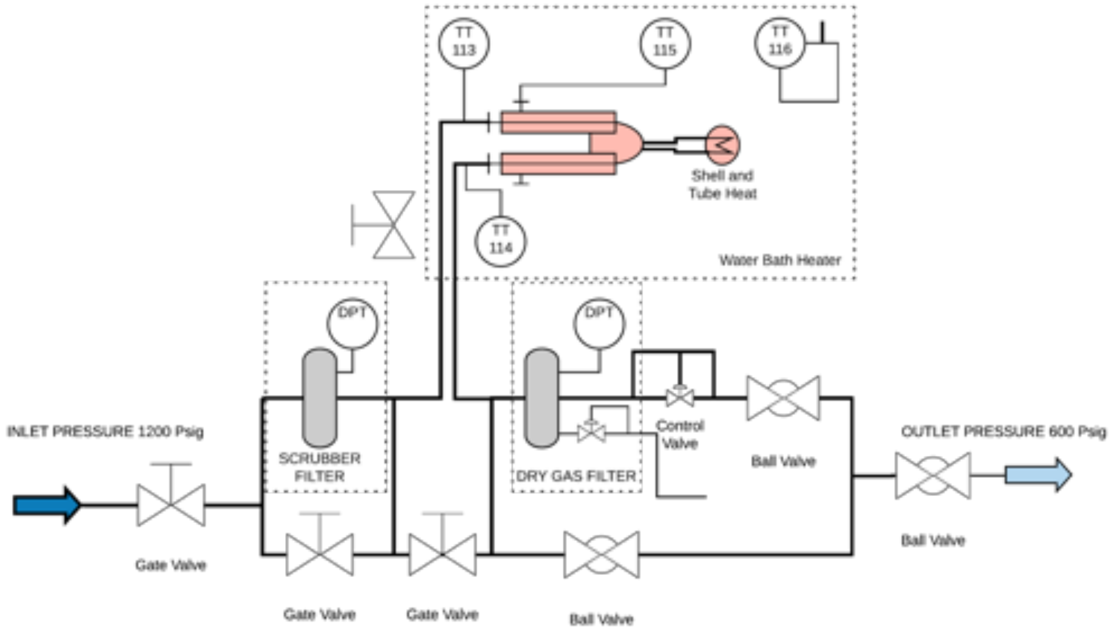


IFog4.0

- IoT integration
- Low latency
- Data privacy
- High Security
- On-Demand installation Application
- Data flow support
- Fast deployments
- Open source
- Follow the RAMI4.0
- Supporting various Industrial Protocols (ProfiNet, Modbus, OPC-UA)



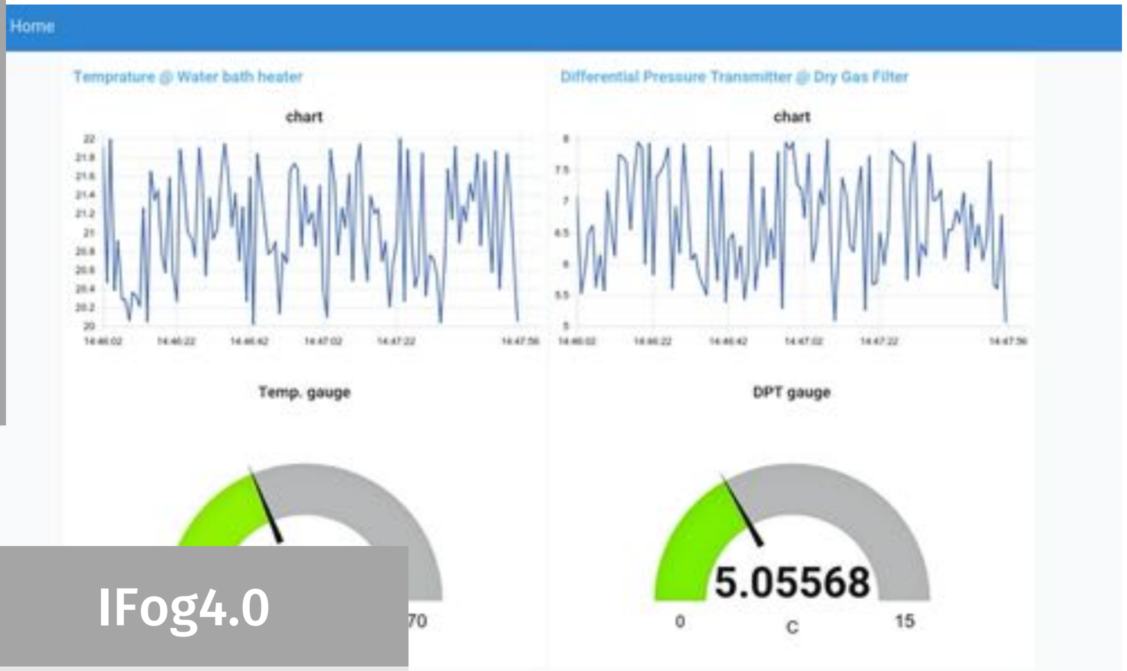
TESTBED

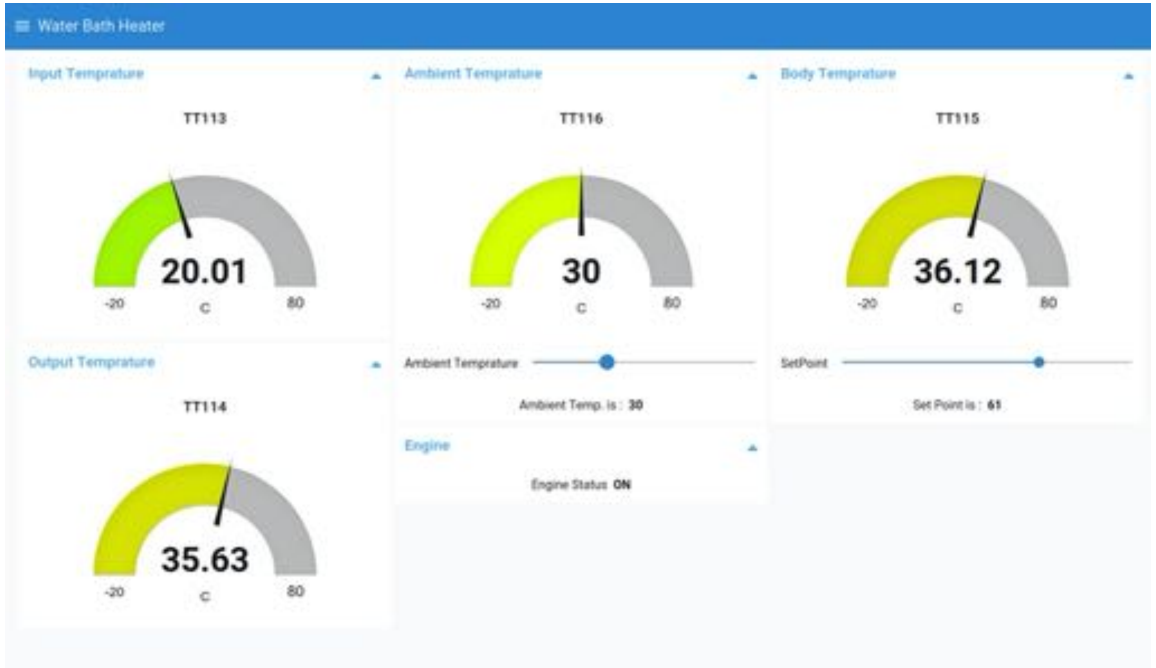


GAS STATION

IFog 4.0: usecase

IFog4.0





IFog4.0

Fast Deployments
Data privacy
Low Latency

IFog 4.0: Data visualization

TSCH WSN

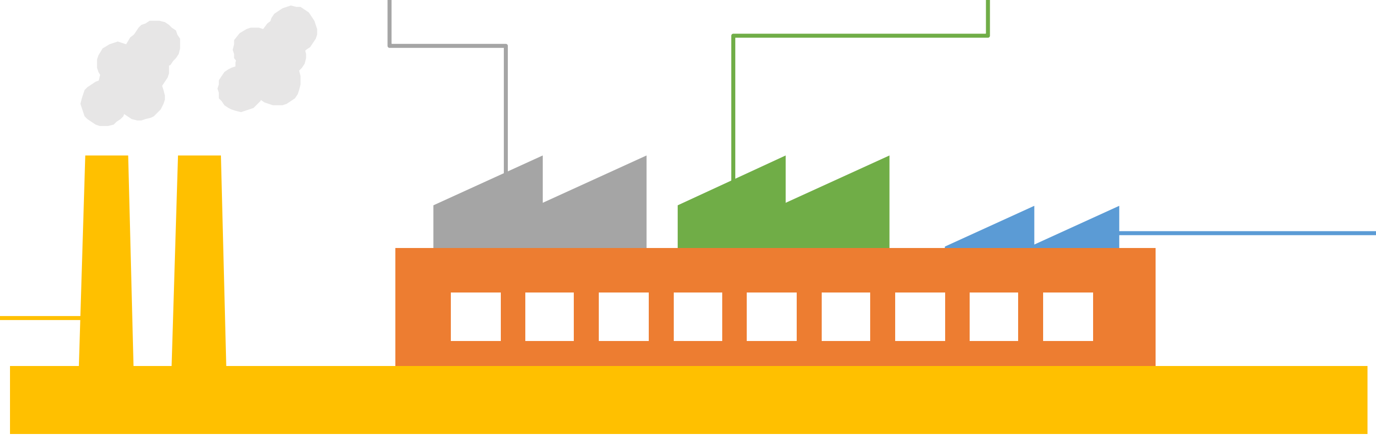
Solutions for Industry 4.0 communication issues

OPC-IoT platform
IoT adoption
Standardization
Performance analysis

IFog4.0
Fast Deployments
Data privacy
Low Latency

TSCH WSN Model
Deployment issue
Performance analysis

TSCH Predictor
Deployment issue
Performance analysis

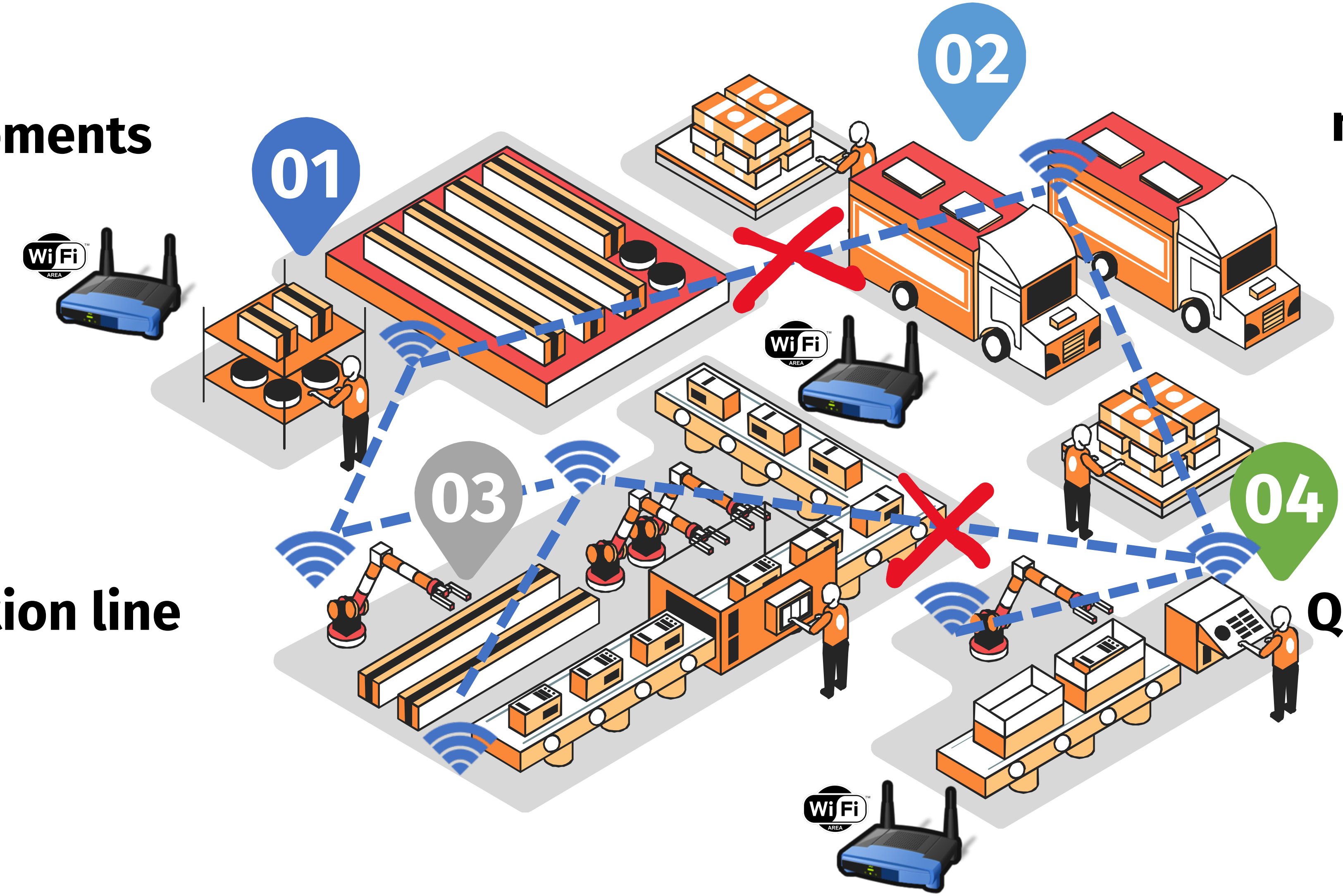


TSCH WSN Model

WSN challenges

01
Stock managements

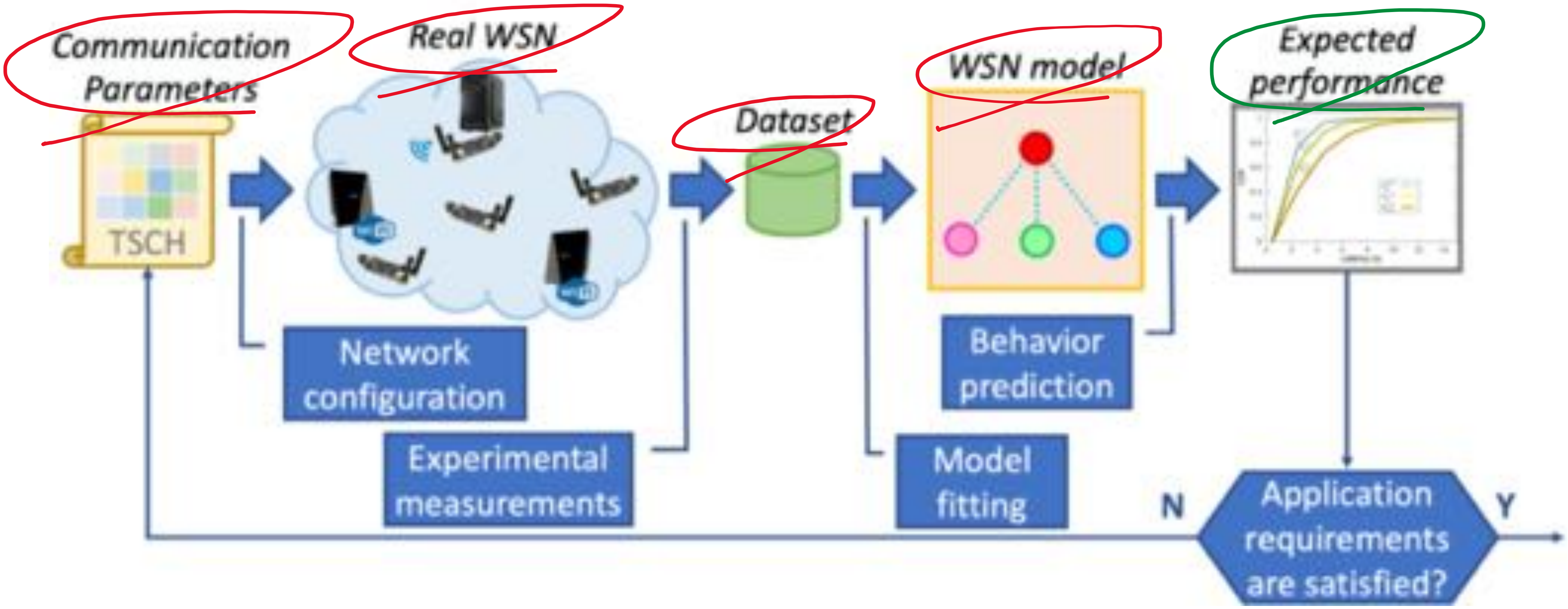
02
Supply managements



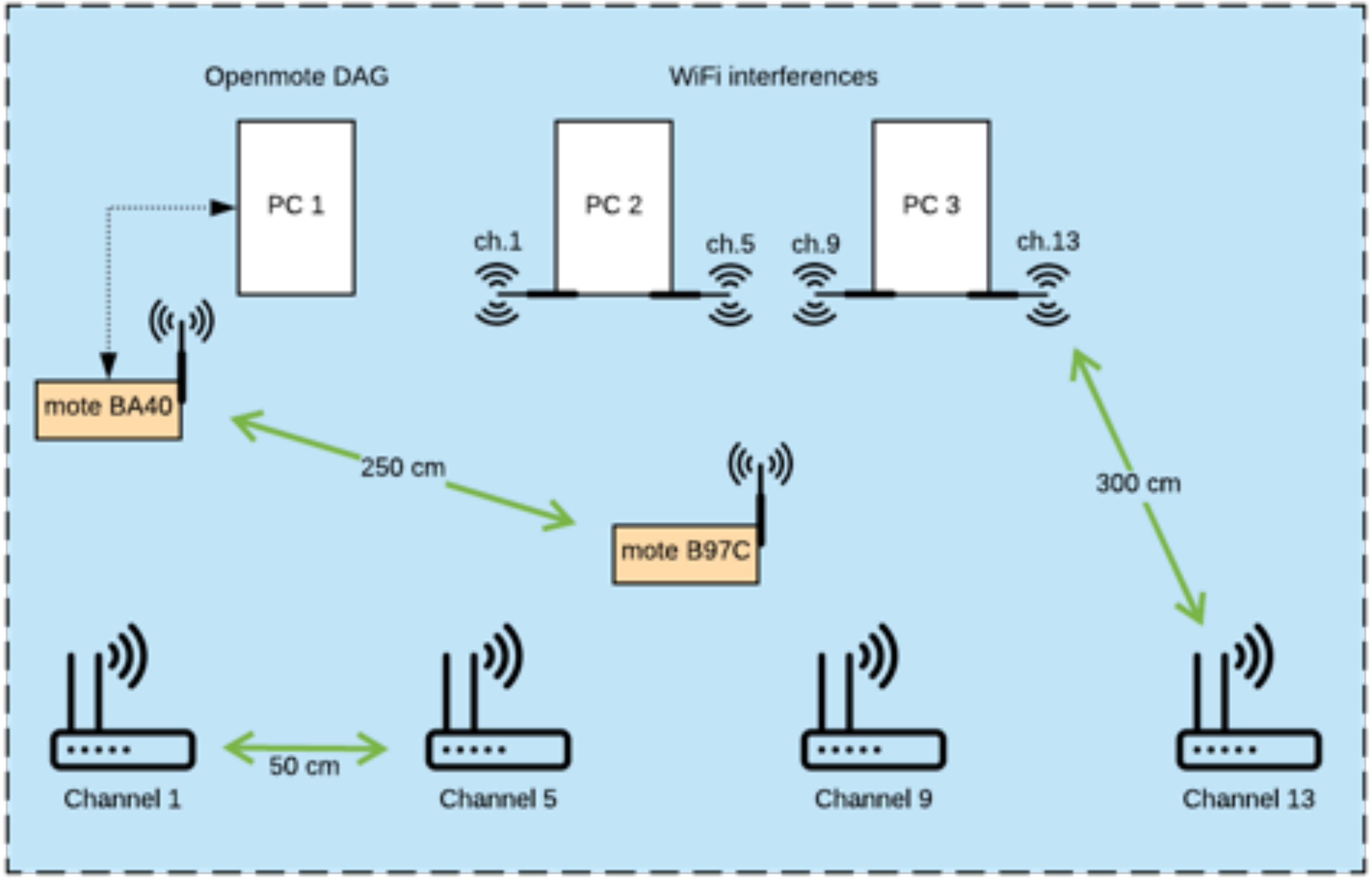
03
Production line

04
Quality Control

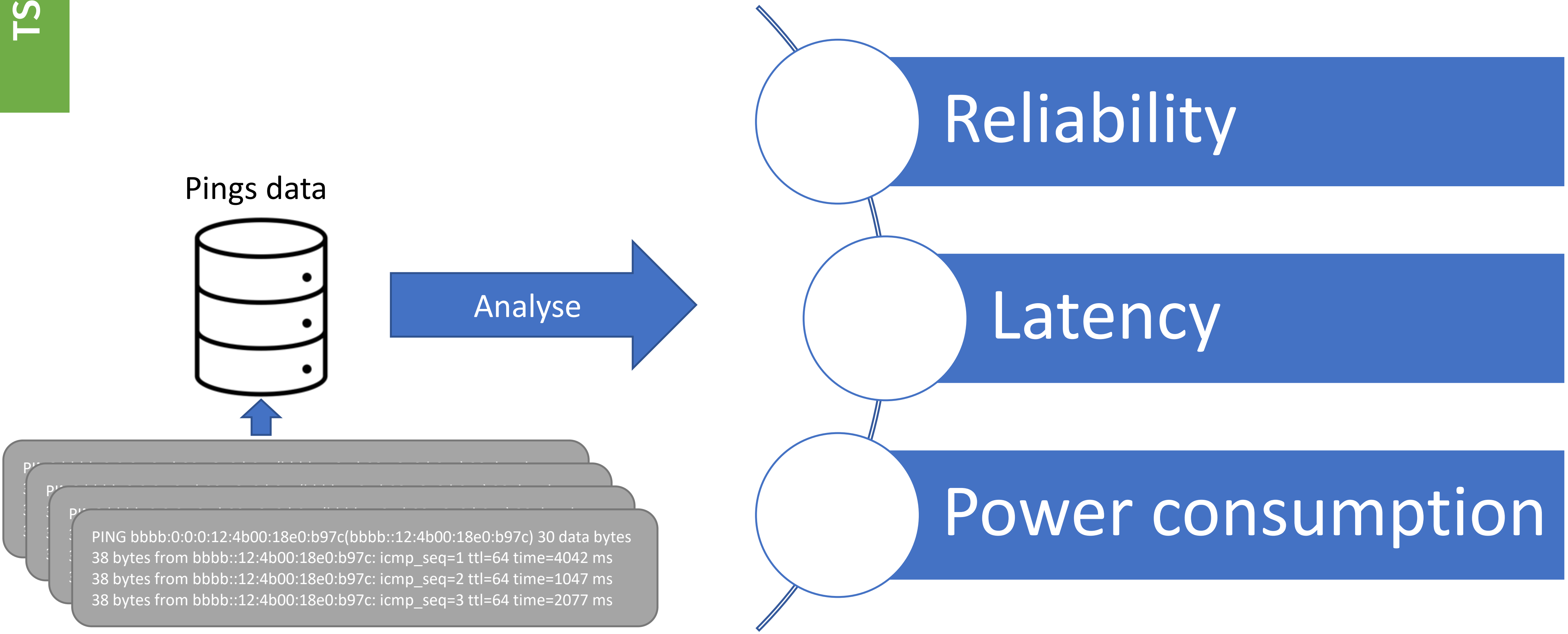
Modeling of the TSCH WSN against Wi-Fi



Testbed setup



Mathematical model derived from latency



TSCH WSN

Performance evaluation

Performance vs. slotframe length

Variation N_{slot}

	Latency								Reliability			Power Consumption				
N_{slot}	d_{min}	μ_d	σ_d [s]	d_{p99}	d_{max}	$\hat{n}_{tra}$ [#]	$\hat{\mu}_d$ [s]	Max_d [s]	P_{lost}	ϵ	$1-\epsilon_{pkt}$	f_{tra} $[\cdot 10^{-5}]$	f_{listen} $[\cdot 10^{-4}]$	P μW	$\hat{f}_{tra}$ $[\cdot 10^{-5}]$	$\hat{f}_{listen}$ $[\cdot 10^{-4}]$
11	0.212	0.409	0.194	1.231	1.438	2.34	0.399	7.040	0.0	0.148	12-nines	2.00	90.70	1262.8	1.95	90.71
31	0.491	0.982	0.431	2.301	3.419	2.27	0.969	19.840	0.0	0.119	14-nines	1.91	32.06	453.0	1.89	32.06
51	0.258	1.024	0.649	3.007	3.054	2.25	1.021	32.640	0.0	0.110	15-nines	1.88	19.41	278.3	1.87	19.42
91	0.497	1.741	1.046	4.861	5.397	2.25	1.858	58.240	0.0	0.110	15-nines	1.87	10.80	159.4	1.87	10.80
101	0.352	2.046	1.588	8.764	10.457	2.28	1.936	64.640	0.0	0.124	14-nines	1.95	9.70	144.7	1.90	9.71
151	2.877	5.036	1.755	8.846	14.557	2.25	5.135	96.640	0.0	0.110	15-nines	1.85	6.44	99.0	1.87	6.43
201	0.726	4.216	2.880	12.131	14.050	2.36	4.193	128.640	0.0	0.153	12-nines	1.97	4.78	76.7	1.97	4.78

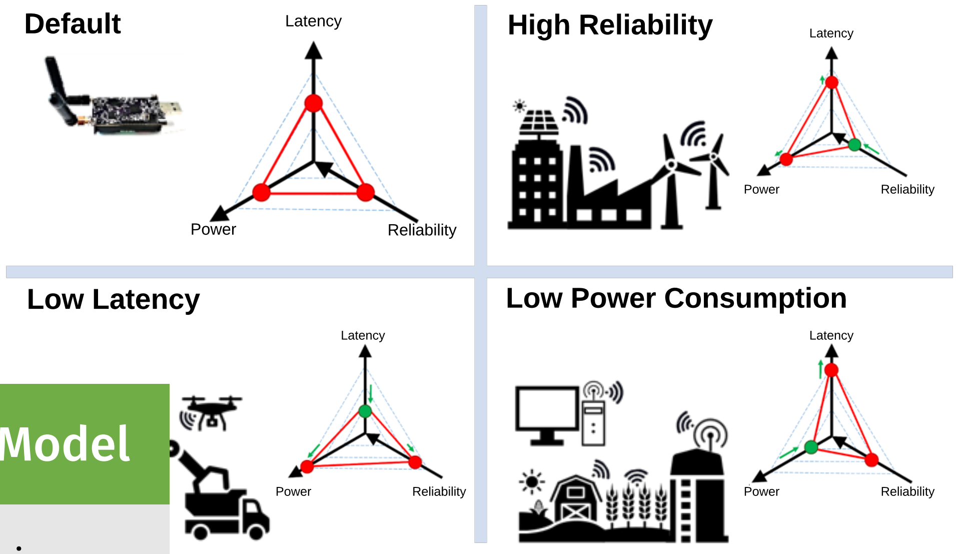
Performance vs. retry limit

Variation N_{tries}

	Latency								Reliability			Power Consumption				
N_{tries}	d_{min}	μ_d	σ_d [s]	d_{p99}	d_{max}	$\hat{n}_{tra}$ [#]	$\hat{\mu}_d$ [s]	Max_d [s]	P_{lost}	ϵ	$1-\epsilon_{pkt}$	f_{tra} $[\cdot 10^{-5}]$	f_{listen} $[\cdot 10^{-4}]$	P μW	$\hat{f}_{tra}$ $[\cdot 10^{-5}]$	$\hat{f}_{listen}$ $[\cdot 10^{-4}]$
2	0.496	1.851	1.015	4.441	5.377	2.17	1.861	8.080	0.017	0.0963	0.98154	1.82	9.71	144.1	1.82	9.71
4	0.342	1.853	1.272	6.066	6.090	2.24	1.850	16.160	0.0	0.1102	0.99971	1.88	9.71	144.3	1.87	9.71
6	0.387	2.031	1.323	6.906	7.447	2.32	2.048	24.240	0.0	0.1388	0.99999	1.93	9.70	144.5	1.93	9.70
8	0.726	2.320	1.558	8.255	9.890	2.27	2.285	32.320	0.0	0.1197	7-nines	1.92	9.70	144.5	1.89	9.71
16	0.352	2.046	1.588	8.764	10.457	2.28	1.936	64.640	0.0	0.1244	14-nines	1.95	9.70	144.6	1.90	9.71

TSCH WSN

Performance evaluation



- Default config
- High Reliability
- Low Latency
- Low Power Consumption

TSCH WSN Model

Deployment issue
Performance analysis

Trade off between different config

Configuration			Latency						Reliability			Power Consumption		
Condition	N_{slot}	N_{tries}	d_{min}	μ_d	σ_d [s]	d_{p99}	d_{max}	Max_d [s]	P_{lost}	ϵ	$1-\epsilon_{pkt}$	f_{tra} $[\cdot 10^{-5}]$	f_{listen} $[\cdot 10^{-4}]$	P μW
Default	101	16	0.528	2.115	1.310	6.579	11.049	64.640	0.0	0.125	14-nines	1.91	9.71	144.4
High Reliability	101	24	1.470	3.090	1.320	7.450	9.360	96.960	0.0	0.132	20-nines	1.92	9.71	144.5
Low Latency	11	3	0.159	0.336	0.135	0.780	1.023	1.320	0.0042	0.142	0.9942	1.92	90.71	1262.4
Low Power Cons.	201	16	2.565	5.535	2.461	13.637	22.366	128.640	0.0	0.112	14-nines	1.92	4.78	76.5
Default (15-days)	101	16	0.522	2.114	1.289	6.393	12.382	64.640	0.0	0.126	14-nines	1.90	9.71	144.5

Solutions for Industry 4.0 communication issues

OPC-IoT platform

IoT adoption
Standardization
Performance analysis

IFog4.0

Fast Deployments
Data privacy
Low Latency

TSCH WSN Model

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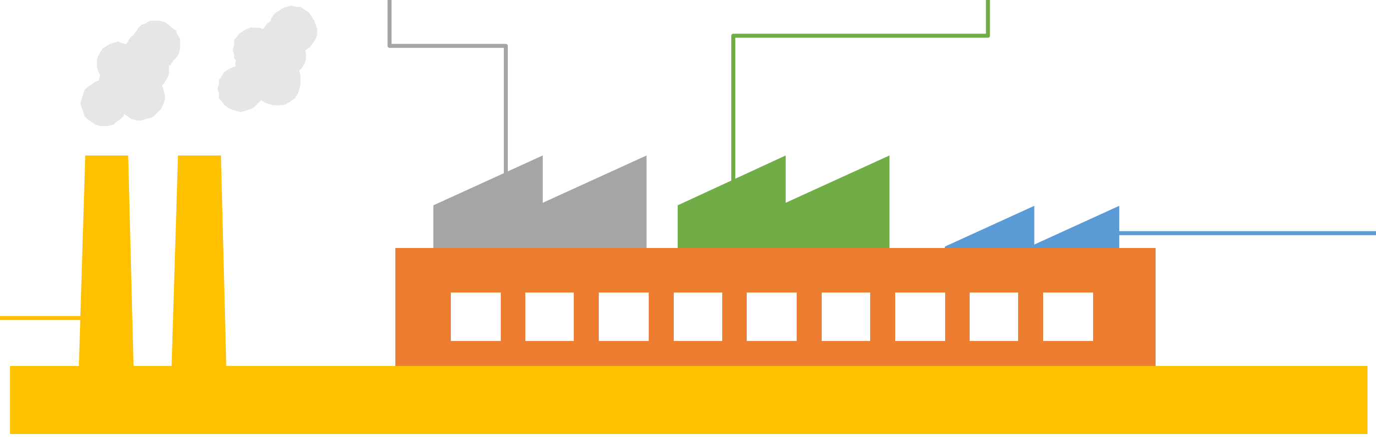
Performance analysis

TSCH Predictor

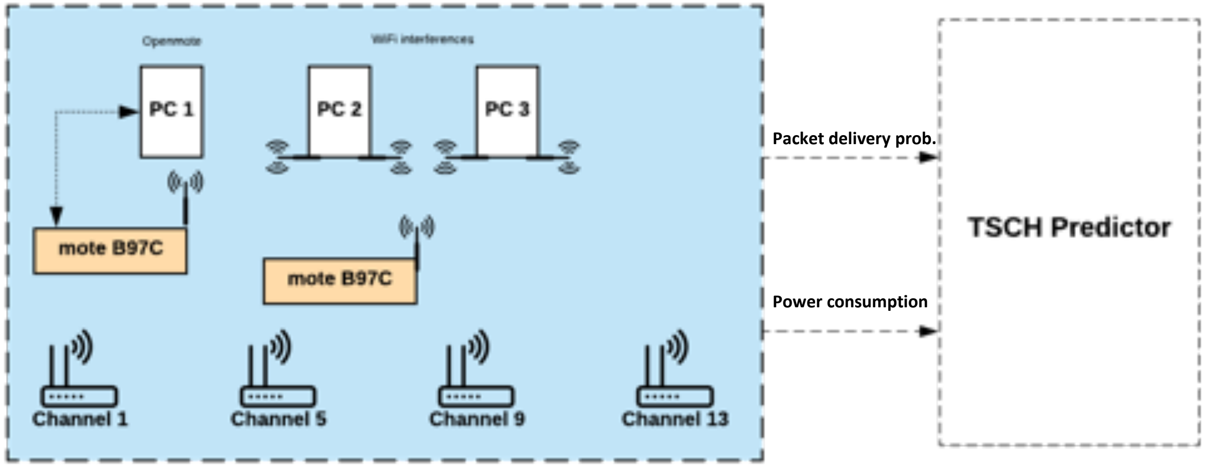
Deployment issue
Performance analysis



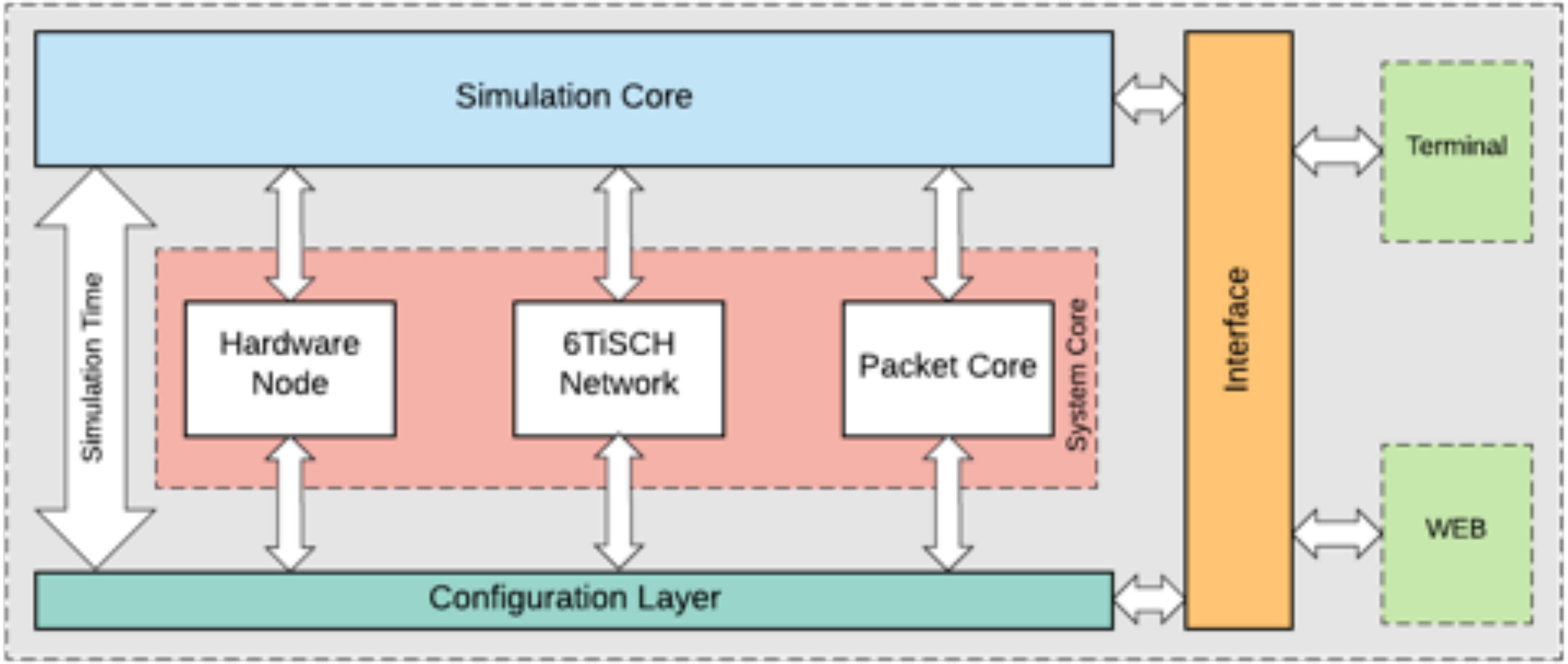
TSCH Predictor

TSCH predictor

- Easy to use
- Uses the packet delivery probability.
- It could predict performance indicator
- Perform longer experiment with no limitation
- Easy to change the network parameters



TSCH predictor Software Architecture



TSCH Predictor

Performance evaluation

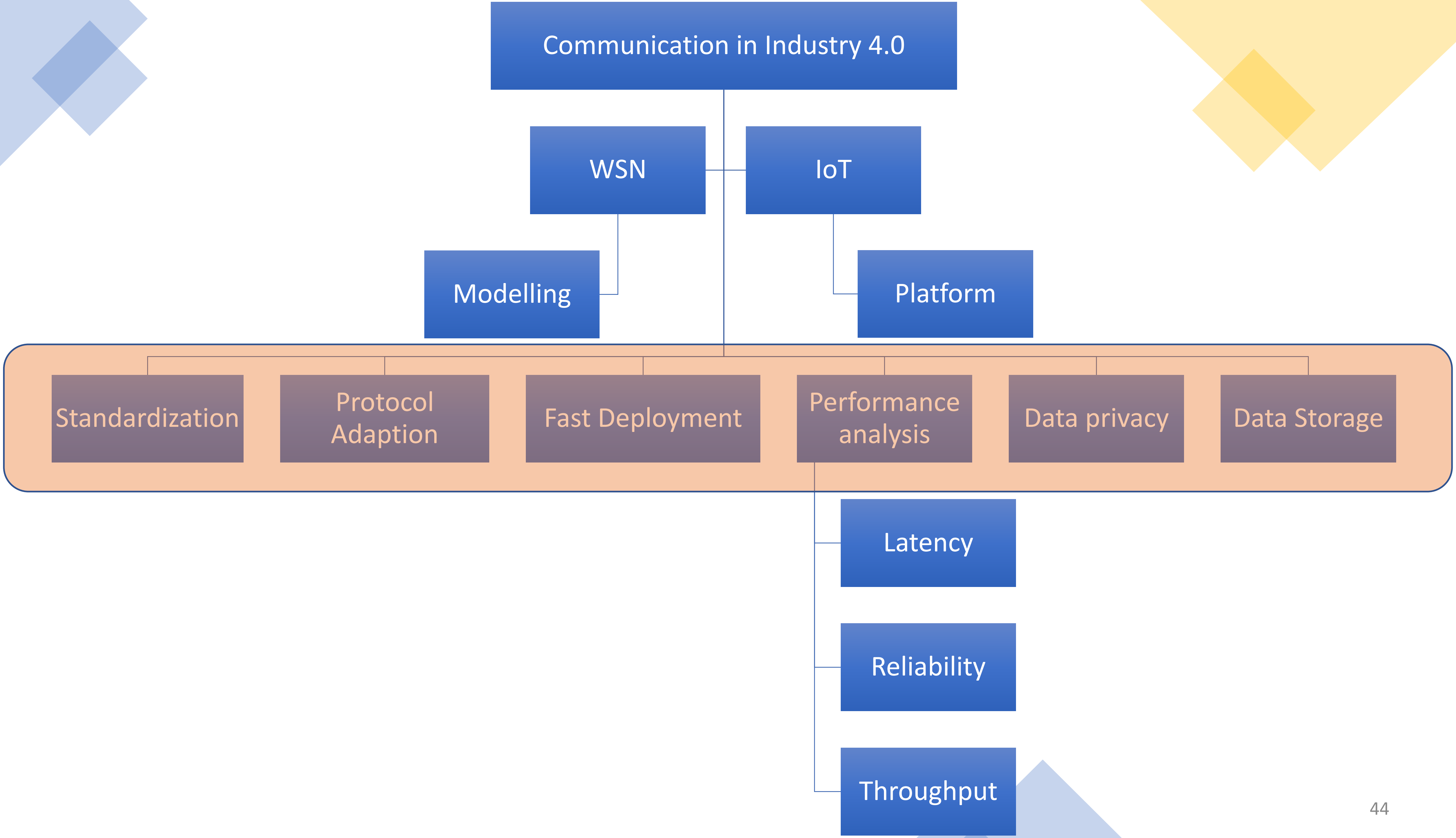
TSCH Conf.		Latency								Reliability			Power Consumption				
N_{slot}	N_{tries}	d_{min}	μ_d	σ_d [s]	d_{p99}	d_{max}	$\hat{n}_{tra}$ [#]	$\hat{\mu}_d$ [s]	Max_d [s]	P_{lost}	ϵ	$1-\epsilon_{pkt}$	f_{tra} [$\cdot 10^{-5}$]	f_{listen} [$\cdot 10^{-4}$]	P [μW]	$\hat{f}_{tra}$ [$\cdot 10^{-5}$]	$\hat{f}_{listen}$ [$\cdot 10^{-4}$]
Real data with Openmote B																	
11	3	0.159	0.335	0.134	0.780	1.023	2.32	0.338	1.320	0.4166	0.1428	0.9941	1.93	90.7	1262.49	1.94	90.71
101	16	0.522	2.117	1.29[illegible]	6.398	1[illegible].382	2.29	2.12	64.640	0	0.1263	1	1.91	9.71	144.494	1.91	9.71
101	24	1.47	3.089	1.32	7.45	9.36	2.31	3.10	96.96	0	0.1323	1	1.92	9.71	144.554	1.92	9.71
201	16	2.565	5.534	2.46	13.637	22.366	2.25	5.60	128.64	0	0.1125	1	1.92	4.78	76.5805	1.87	4.79
Simulation with TSCH predictor																	
11	3	0.160	0.329	0.142	0.780	1.240	2.31	0.339	1320	0.5761	0.1435	0.9940	1.93	90.7	1262.53	1.93	90.71
101	16	0.520	2.105	1.30[illegible]	6.420	[illegible]4.500	2.29	2.12	64.640	0	0.1266	1	1.91	9.71	144.496	1.91	9.71
101	24	1.46	3.078	1.334	7.440	18.400	2.31	3.09	96.96	0	0.1327	1	1.92	9.71	144.551	1.92	9.71
201	16	2.58	5.581	2.443	13.98	30.18	2.25	5.61	128.64	0	0.1127	1	1.88	4.79	76.3954	1.88	4.79

TSCH Predictor

Deployment issue
Performance
analysis

- Easy to use
- Uses the packet delivery probability.
- It could predict performance indicator
- Perform longer experiment with no limitation
- Easy to change the network parameters

Conclusions & Future work


Communication in Industry 4.0
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Reliability
Throughput

Conclusions

OPC-IoT platform

- Overcomes standardization complexity
- Based RAMI 4.0
- Overcomes compatibility issue
- Analyzing the performance indicator for proposed IoT
- Opensource solution for SME

IFog 4.0

- Overcomes centralization complexity/issues
- Latency issue
- Privacy/Data ownership
- Fast deployment
- Opensource solution for SME

TSCH WSN Model

- Analyzes behavior of single and multi hop topologies
- Proposes model to predict TSCH WSN performance indicator
- Proposes method to config/set up fast and easier TSCH network for SME
- Proposes method to choose the network parameter with requested indicator

TSCH Predictor

- Overcomes simulation complexity for SME
- Easy to perform long experiments
- Predicts performance indicator
- Proposes the Web interface beside the command line interface

Future work

- Working on the extension of the TSCH Predictor and developing new futures.
- Proposing automated technic to select a best network parameters based on the background traffic
- Developing the optimization technic for WSN parameter selection.
- Performing more realistic experiments with IFog4.0
- Analyze the performance indicator for IFog4.0
- Developing MQTT solution for IoT platform and compare it with OPC-UA

THANKS

It is a question time!

mohammad.ghazivakili@polito.it

www.ghazivakili.com

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Thank you

Thank you so much for your time

Backup Slide

Appendix A: Journal Paper

- Evaluating and Modeling IEEE 802.15.4 TSCH Resilience against Wi-Fi Interference in New-Generation Highly-Dependable Wireless Sensor Networks / Cena, Gianluca; Demartini, Claudio G.; Vakili, Mohammad Ghazi; Scanzio, Stefano; Valenzano, Adriano; Zunino, Claudio. - In: AD HOC NETWORKS. - ISSN 1570-8705. - STAMPA. - 106:102199(2020).
- Wireless Sensor Networks and TSCH: a compromise between Reliability, Power Consumption and Latency / Scanzio, Stefano; Vakili, Mohammad Ghazi; Cena, Gianluca; Demartini, Claudio Giovanni; Montrucchio, Bartolomeo; Valenzano, Adriano; Zunino, Claudio. - In: IEEE ACCESS. - ISSN 2169-3536. - ELETTRONICO. - 8(2020), pp. 167042-167058.
- Quantum Pliers Cutting the Blockchain / Giusto, Edoardo; Ghazi Vakili, Mohammad; Gandino, Filippo; Demartini, Claudio Giovanni; Montrucchio, Bartolomeo. - In: IT PROFESSIONAL. - ISSN 1520-9202. - ELETTRONICO. - 22:6(2020), pp. 90-96.
- A Densely-Deployed, High Sampling Rate, Open-Source Air Pollution Monitoring WSN / Montrucchio, Bartolomeo; Giusto, Edoardo; Ghazi Vakili, Mohammad; Quer, Stefano; Ferrero, Renato; Fornaro, Claudio. - In: IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY. - ISSN 0018-9545. - ELETTRONICO. - (In corso di stampa).
- A Fuzzy Control System for Energy Efficient Wireless Devices in the Internet of Vehicles / Mario Collotta; Renato Ferrero; Edoardo Giusto; Mohammad Ghazi Vakili; Jacopo Grecuccio; Xiangjie Kong; ; Ilsun You International Journal of Intelligent Systems (Accepted Dec. 7th)

Appendix A: Conferences

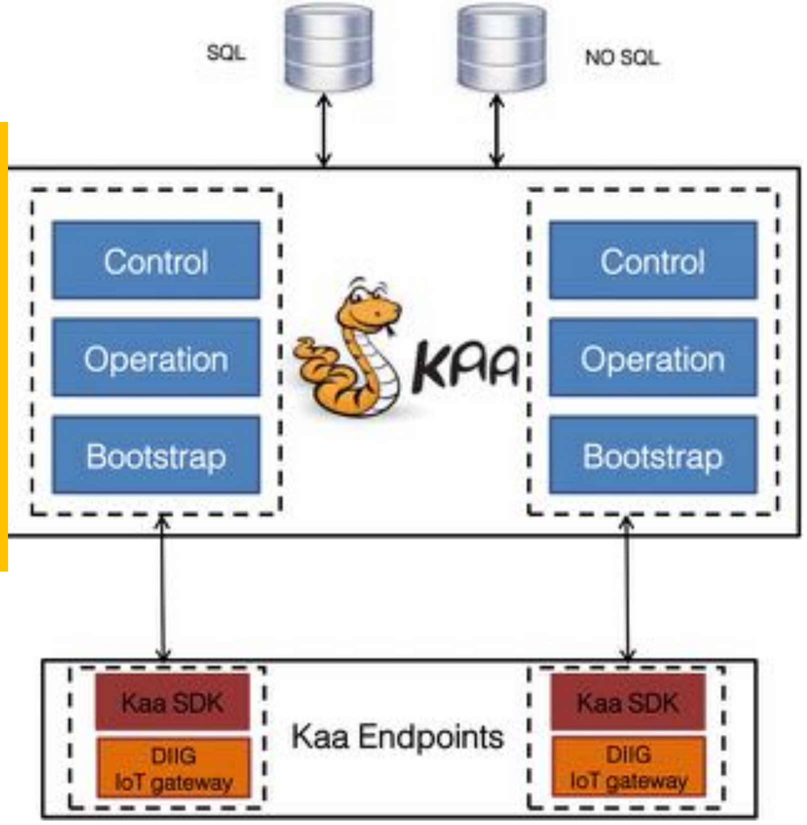
- DIIG: A Distributed Industrial IoT Gateway / Masoud, Hemmatpour; Mohammad, Ghazivakili; Bartolomeo, Montrucchio; Maurizio, Rebaudengo. - ELETTRONICO. - 1(2017), pp. 755-759. ((Intervento presentato al convegno Computer Software and Applications Conference (COMPSAC) tenutosi a Torino nel 4-8 June 2017.
- Industrial data-collector by enabling OPC-UA standard for Industry 4.0 / GHAZI VAKILI, Mohammad; Demartini, CLAUDIO GIOVANNI; Zunino, Claudio. - ELETTRONICO. - (2018), pp. 1-8. ((Intervento presentato al convegno 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS). 2018
- Open Source Fog Architecture for Industrial IoT Automation Based on Industrial Protocols / Ghazi Vakili, Mohammad; Demartini, Claudio; Guerrera, Mauro; Montrucchio, Bartolomeo. - (2019), pp. 570-578. ((Intervento presentato al convegno IEEE 43rd Annual Computer Software and Applications Conference (COMPSAC) Milwaukee, WI, USA, USA.
- Ubiquitous fridge with natural language interaction / Ferrero, Renato; GHAZI VAKILI, Mohammad; Giusto, Edoardo; Guerrera, Mauro; Randazzo, Vincenzo. - ELETTRONICO. - (2019), pp. 404-409. ((Intervento presentato al convegno 2019 IEEE International Conference on RFID Technology and Applications (RFID-TA) tenutosi a Pisa (Italia) nel 25-27 Settembre 2019.

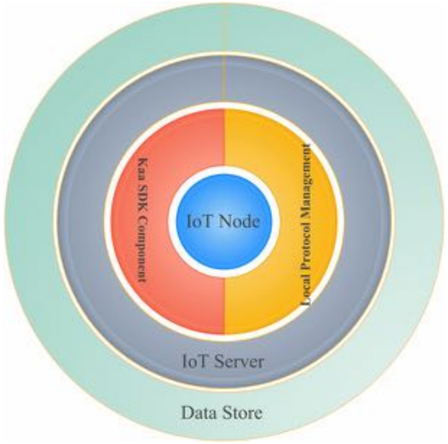
Appendix A: Datasets

- B. Montrucchio, E. Giusto, M. Ghazi Vakili, S. Quer, R. Ferrero, C. Fornaro, "A Densely-Deployed, High Sampling Rate, Open-Source Air Pollution Mon- itoring WSN", IEEEDataPort, August. 2020, doi: https://dx.doi.org/10.21227/m4pb-g538

- S. Scanzio, M. Ghazi Vakili, G. Cena, C. G. Demartini, B. Montrucchio, A. Valenzano, C. Zunino, "Wireless Sensor Networks Dataset (TSCH a Com- promise Between Reliability, Power Consumption, and Latency)", IEEEDat- aPort, Jan. 2021, doi: https://dx.doi.org/10.21227/fg62-bp39

IIoT platform



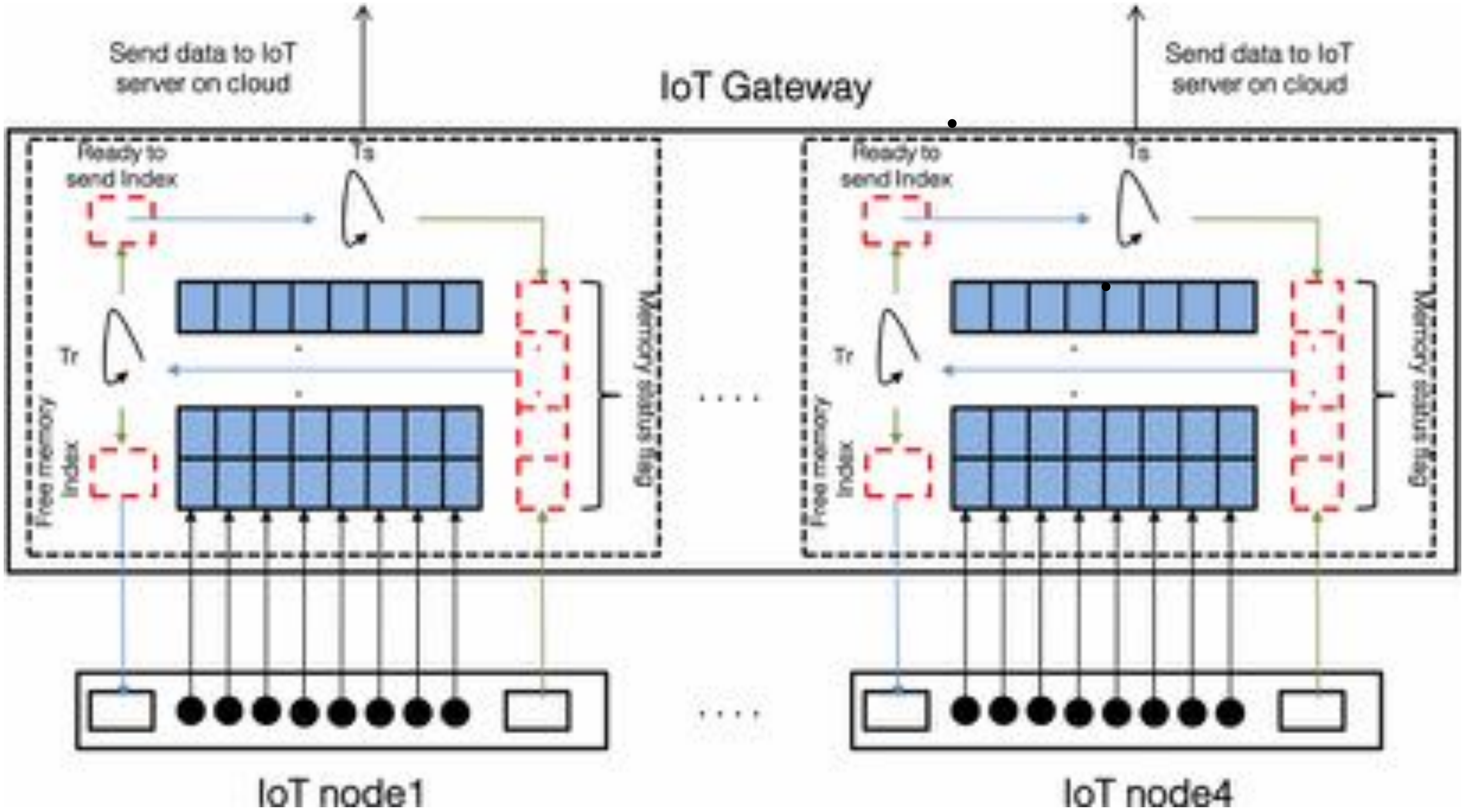


Appendix B. DIIG: A Distributed Industrial IoT Gateway

- The algorithm for IoT gateways proposes to bridge the traditional industrial network and the new paradigm of the Internet of Things network.

  - Read Nodes data on the Profinet and Modbus.
  - Change the protocol.
  - Then push to the IoT Platform with the customized SDK.

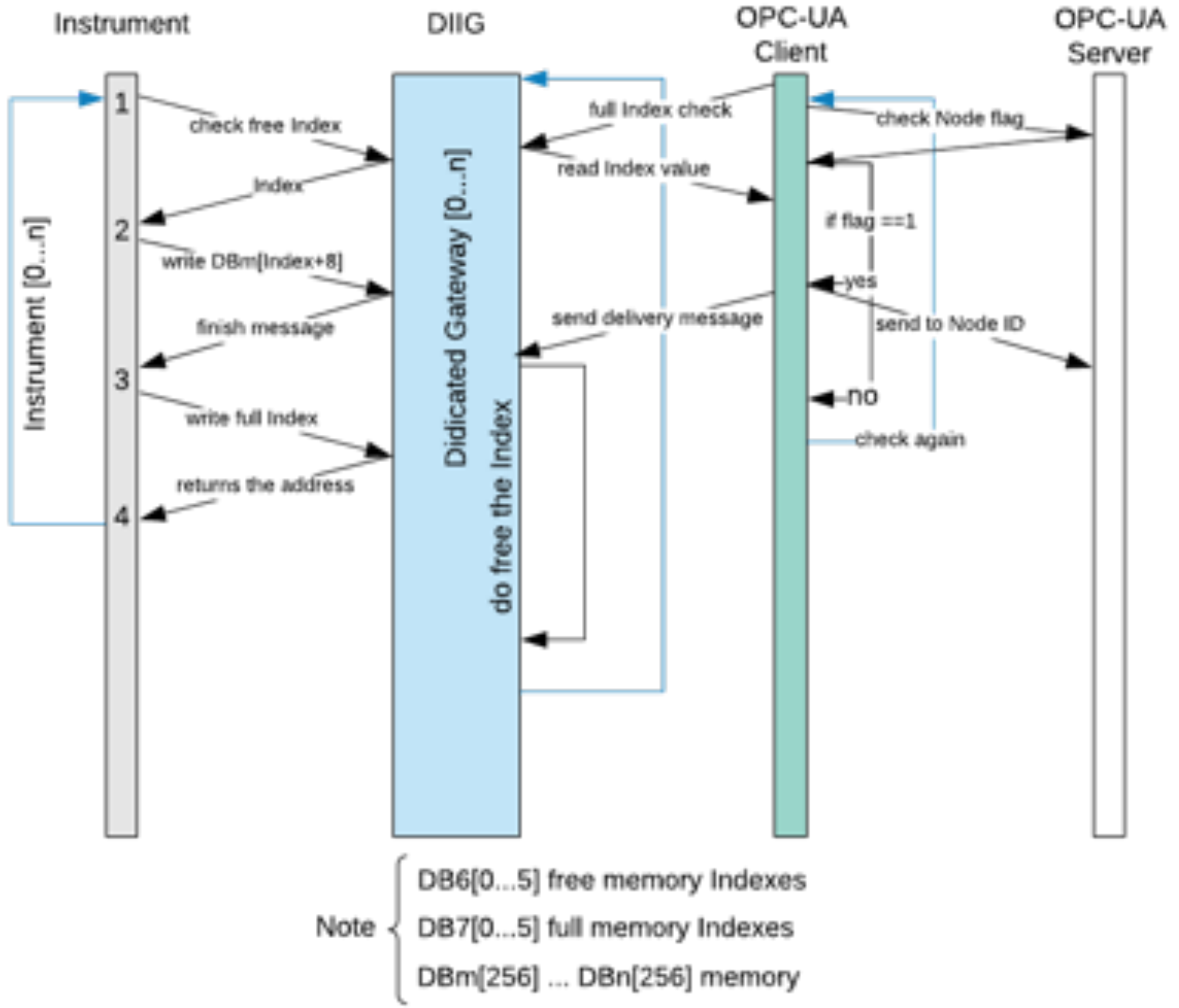
Appendix B. DIIG: A Distributed Industrial IoT Gateway



OPC-IoT platform

Industrial IoT Platform Based on RAMI 4.0

- OPC- gateway algorithm
- Adapting DIIG algorithm with OPC-UA protocol
- Exchange data with Profinel protocol
- Based on service oriented protocol
- Easy to adopt with PLCs, no need to install or using any additional middleware



OPC-IoT platform

Industrial IoT Platform Based on RAMI 4.0

DIIG gateway Algorithm

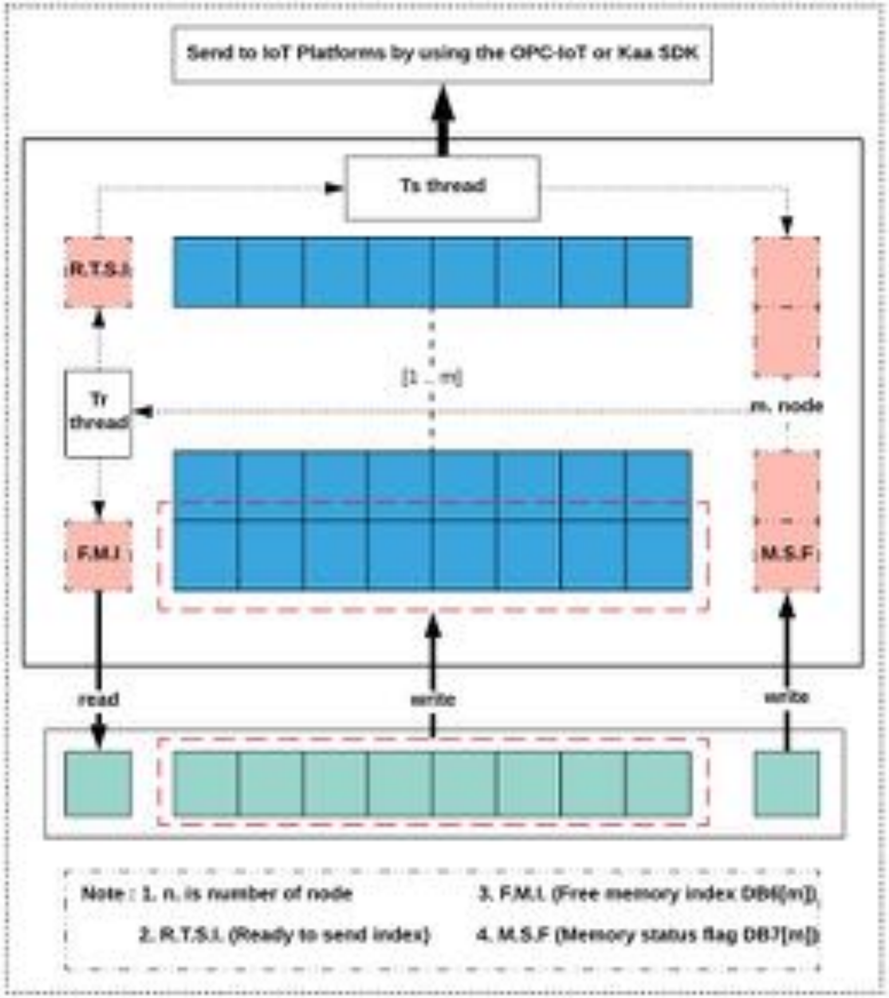
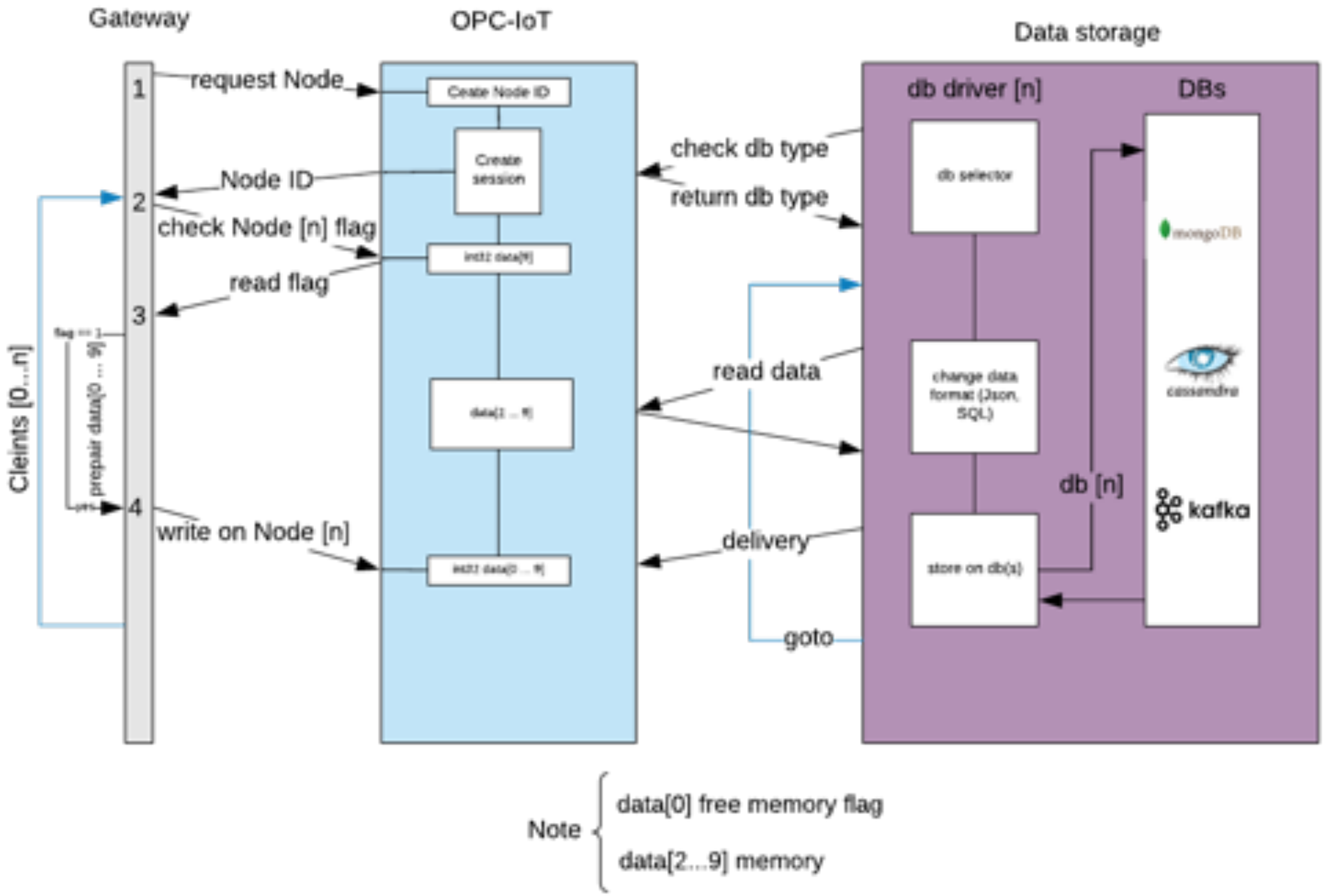


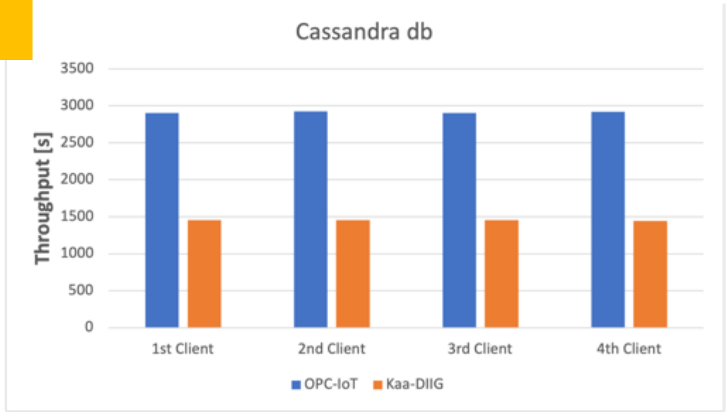
Figure 2.2: DIIG gateway algorithm

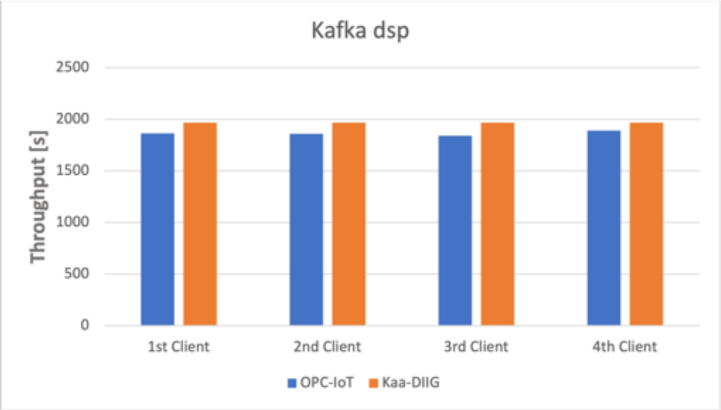
Industrial IoT Platform Based on RAMI 4.0

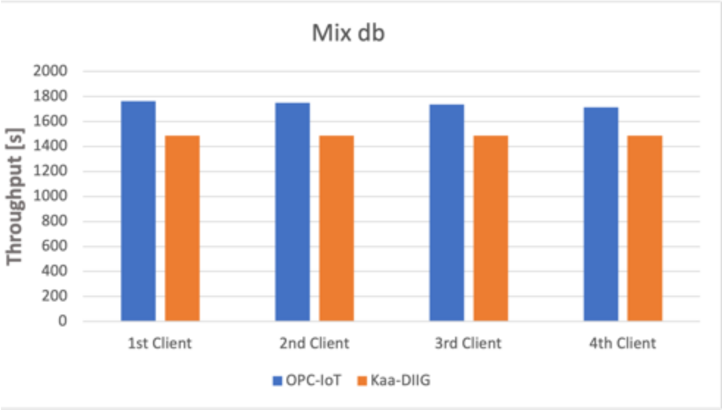
- OPC-IoT Server algorithm
- Implemented based on OPC-UA protocol
- Using 3 different No-SQL database
- Generates one dedicated Node for each IoT device
- Replies delivery message when each message is recorded in the database

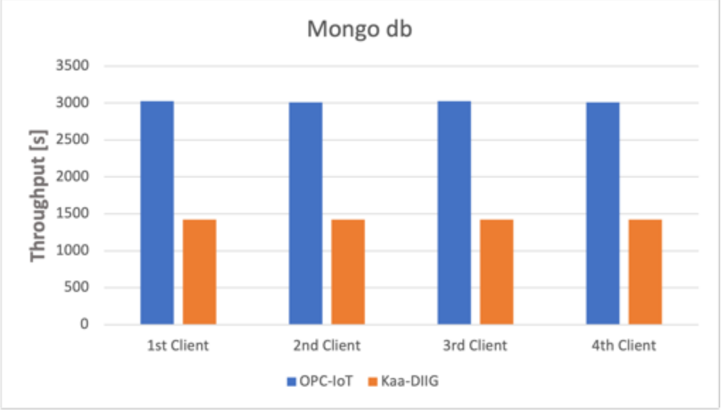


Performance evaluation Fairness



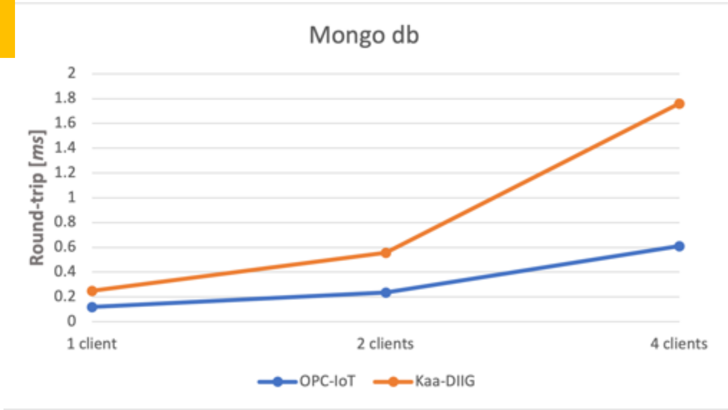


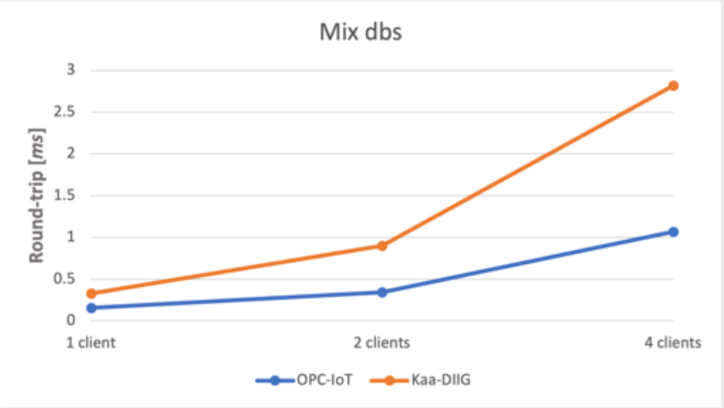


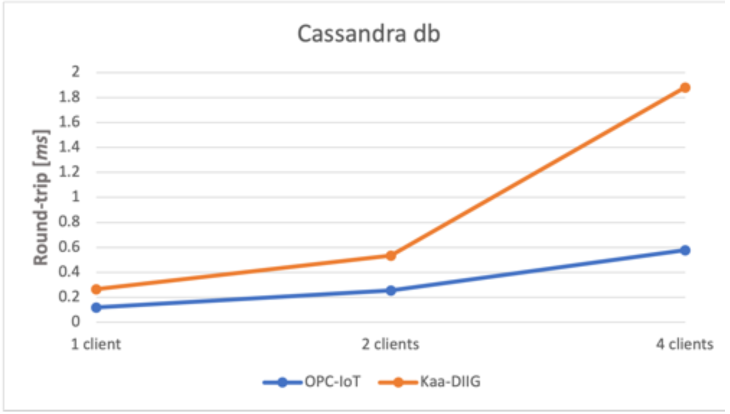


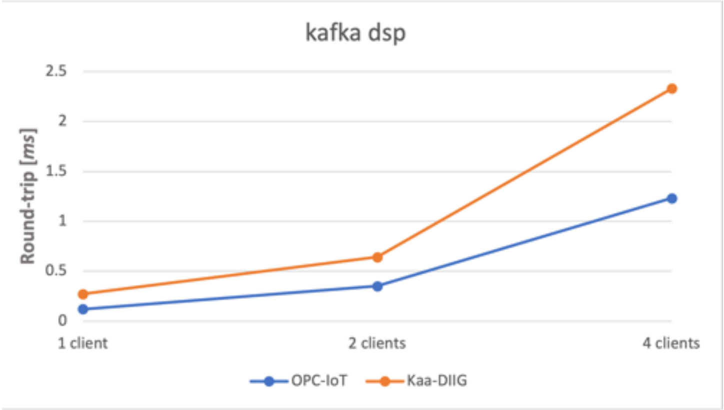
- Result of 100,000 messages that were sent to the server from each client, and the data were stored in various database technologies

Performance evaluation: Roundtrip









Result of 100,000 messages that were sent to the server from each client, and the data were stored in various database technologies

Latency table

KafKa	OPC-IoT			DIIG-KAA		
	min [ms]	avg [ms]	max [ms]	min [ms]	avg [ms]	max [ms]
One client	0.099	0.120	45.448	N/A	0.151	100
Two client	0.116	0.351	48.880	N/A	0.291	292
Four client	0.375	1.231	128.007	N/A	1.098	182

Table 2.1: Round-trip test in $[ms]$ for KafKa with minimum, maximum, and average values

MongoDB	OPC-IoT			DIIG-KAA		
	min [ms]	avg [ms]	max [ms]	min [ms]	avg [ms]	max [ms]
One client	0.124	0.120	35.771	N/A	0.129	7116
Two client	0.102	0.236	31.178	N/A	0.320	5075
Four client	0.084	0.609	23.104	N/A	1.151	13650

Table 2.2: Round-trip test in $[ms]$ for MongoDB with minimum, maximum, and average values

Latency table

Cassandra db	OPC-IoT			DIIG-KAA		
	min [ms]	avg [ms]	max [ms]	min [ms]	avg [ms]	max [ms]
One client	0.133	0.119	35.771	N/A	0.145	247
Two client	0.104	0.255	33.592	N/A	0.278	59
Four client	0.069	0.579	22.840	N/A	1.300	167

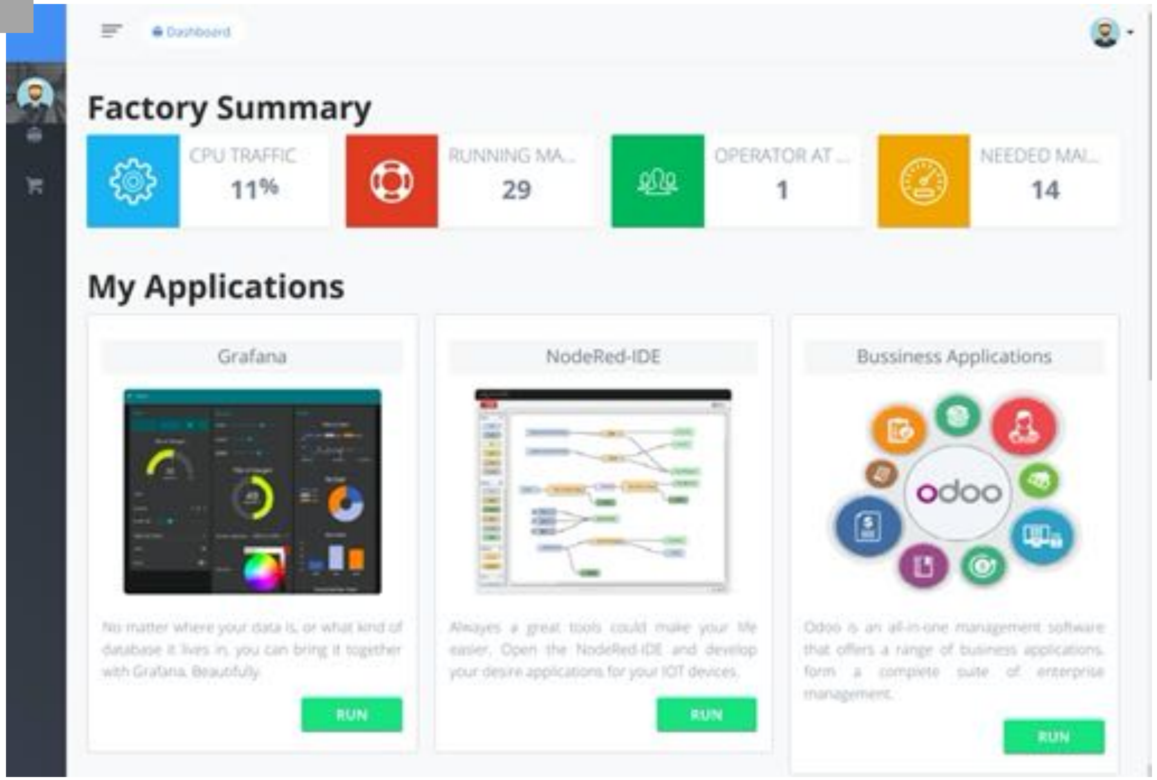
Table 2.3: Round-trip test in [ms] for Cassandra db with minimum, maximum, and average values

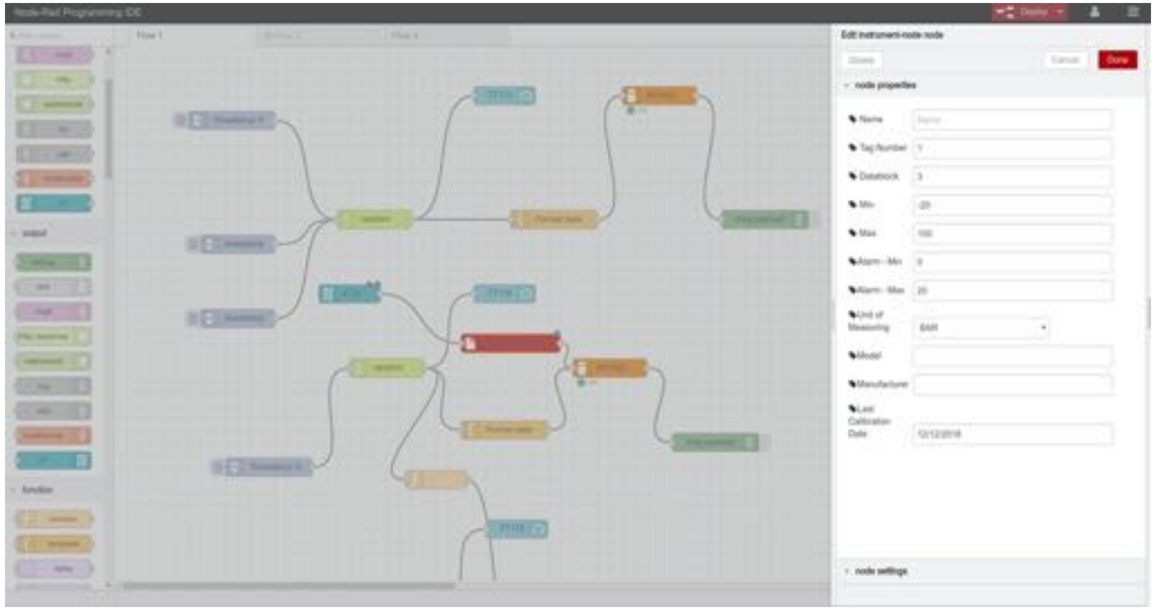
Mix dbs	OPC-IoT			DIIG-KAA		
	min [ms]	avg [ms]	max [ms]	min [ms]	avg [ms]	max [ms]
One client	0.085	0.158	34.966	N/A	0.172	1213
Two client	0.0875	0.345	58.382	N/A	0.553	36689
Four client	0.068	1.069	24.540	N/A	1.750	56183

Table 2.4: Round-trip test in [ms] for Mixed db with minimum, maximum, and average values

IFog 4.0

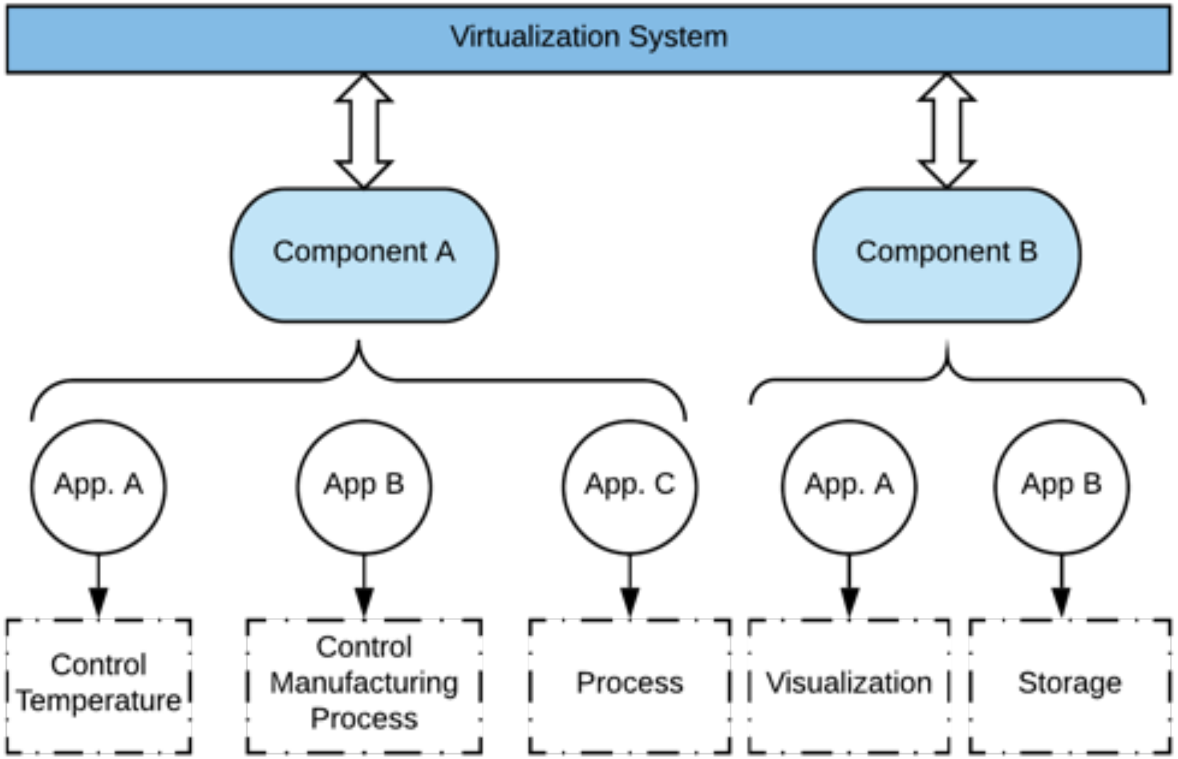
IFog4.0





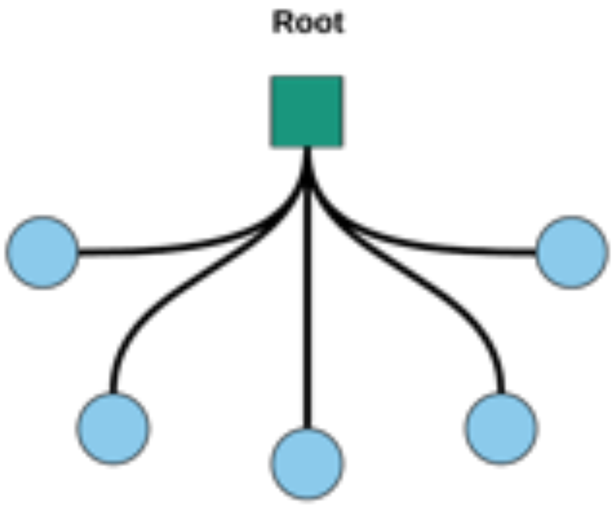
IFog4.0:

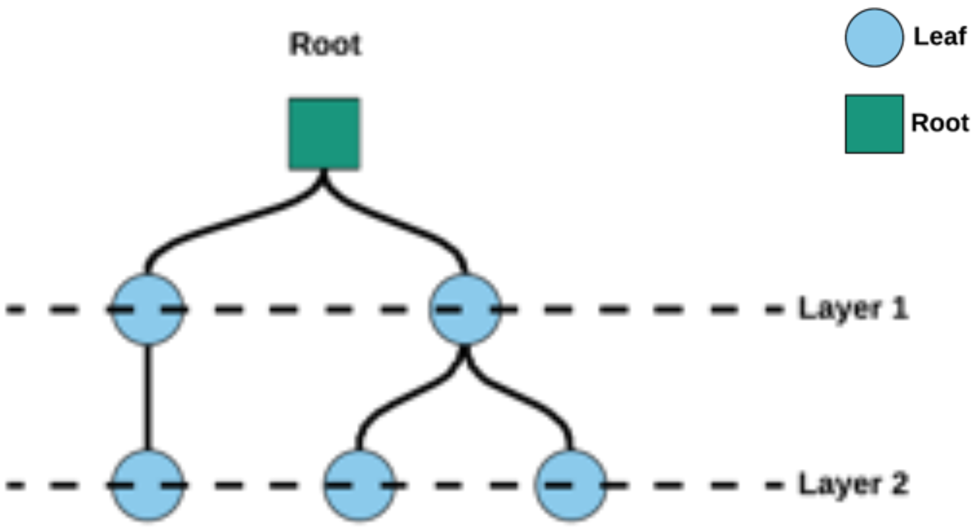
Application & Components



IFog4.0: architecture: components and applications

WSN Topologies





Star / Single Hop

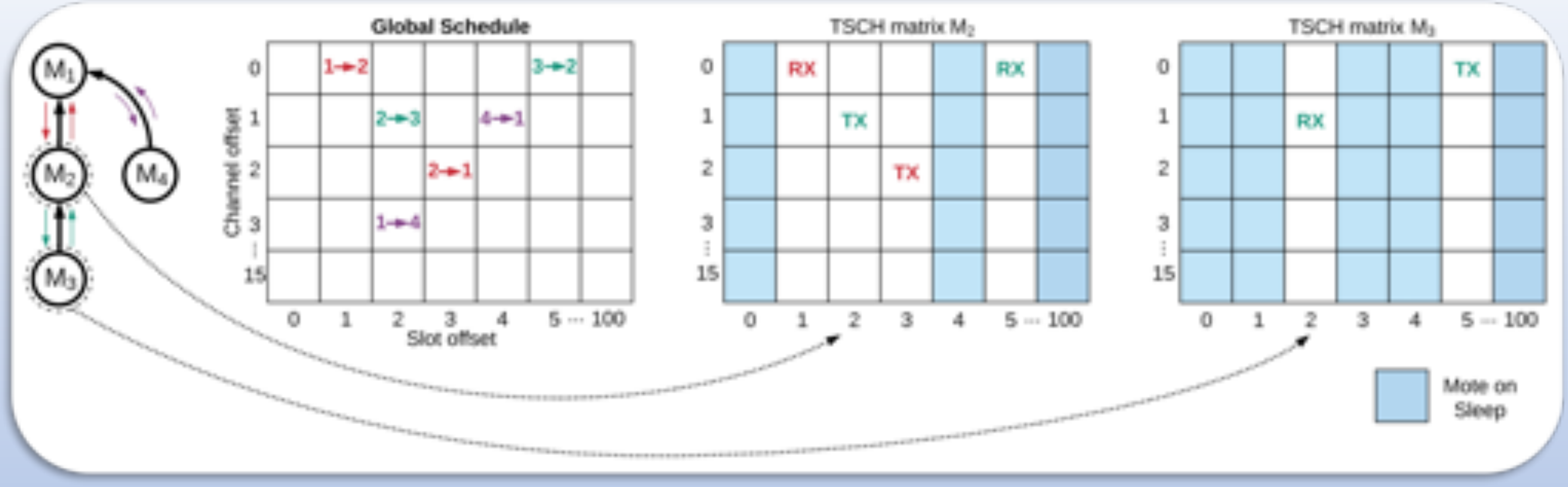
Mesh / Multi Hop

+

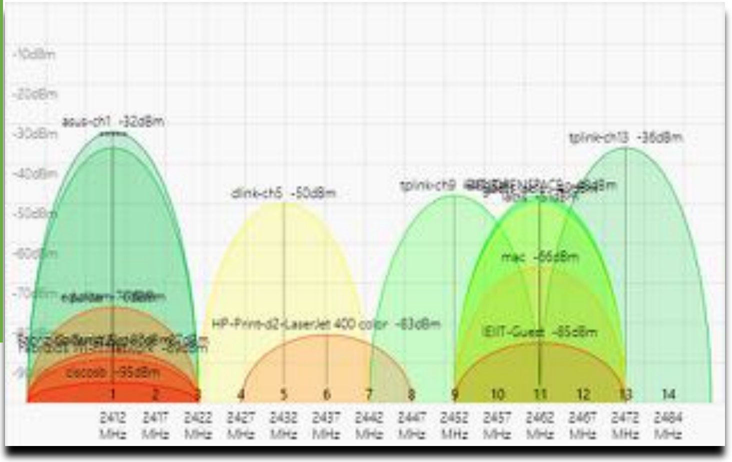
=

6TiSCH

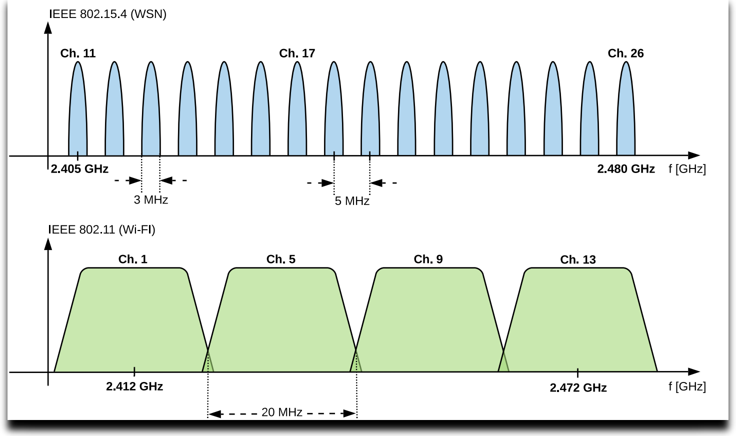
6TiSCH Matrices



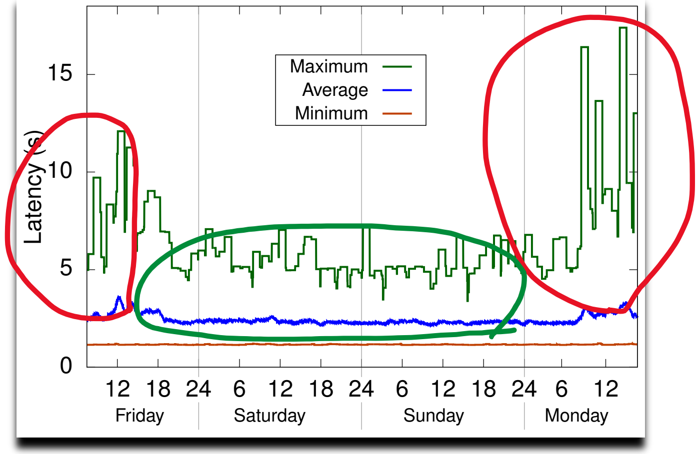
6TiSCH protocol



WiFi network near to WSN



WiFi spectrum vs IEEE802.15.4

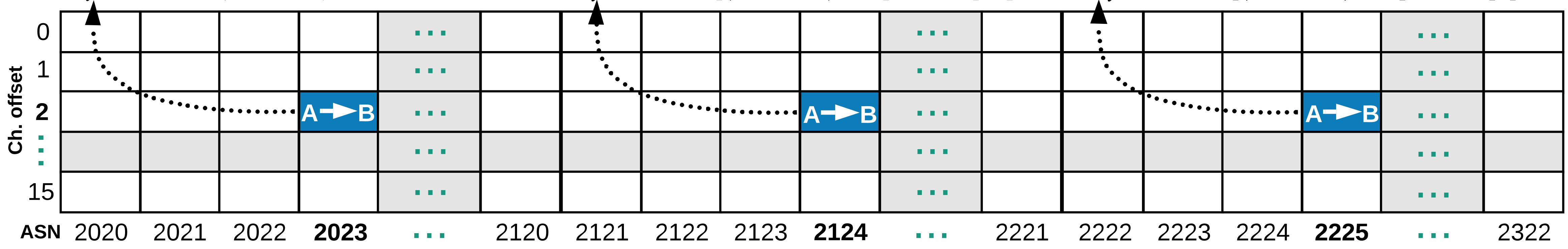


WSN Latency different days

IEEE 802.15.4 vs WiFi Networks

$HopSeqList[] = HSL[] = \{5, 6, 12, 7, 15, 4, 14, 11, 8, 0, 1, 2, 13, 3, 9, 10\}$ $SlotOffset = 3,\ ChOffset = 2$

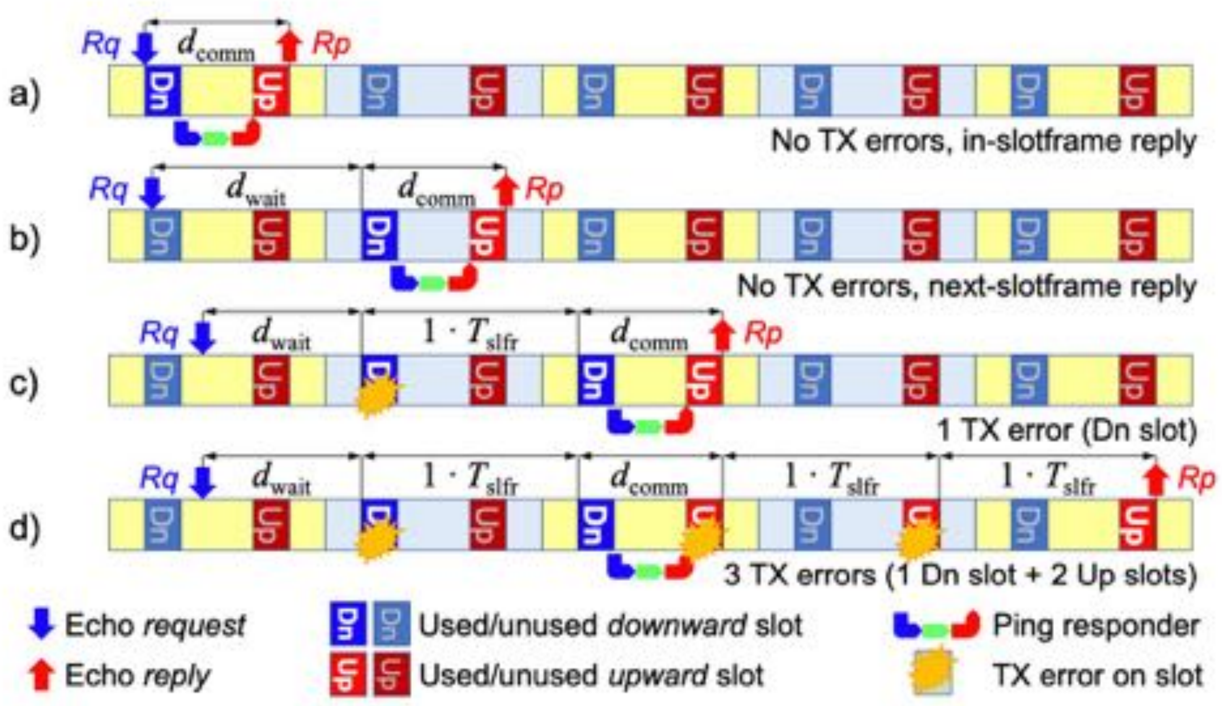
$PhyCh = HSL[(2023+2)\%16] = HSL[9] = \mathbf{0}$ $PhyCh = HSL[(2124+2)\%16] = HSL[14] = \mathbf{9}$ $PhyCh = HSL[(2225+2)\%16] = HSL[3] = \mathbf{7}$



$$PhyCh = HopSeqList[(ASN + ChOffset)\%HopSeqLen]$$

Channel Hopping in IEEE 802.15.4 Networks

Single Hop Latency



- Single-hop request-response transaction in TSCH

Multi Hop Latency

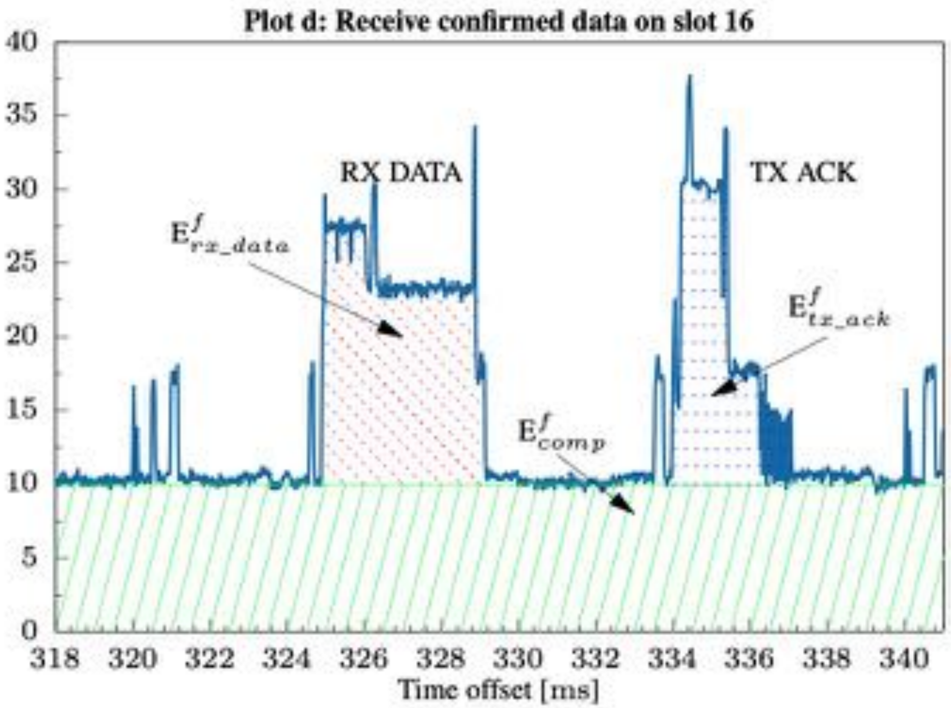
The example of request/response iteration in TSCH

$$
\begin{aligned}
\text{Max}_d &= N_{hop} \cdot N_{tries} \cdot T_{sframe}. \\
&= N_{hop} \cdot N_{tries} \cdot (N_{slot} \cdot T_{slot}) .
\end{aligned}
$$

$$T_{app} \geq \text{Max}_d / N_{hop} = N_{tries} \cdot T_{sframe}.$$

No queuing req.

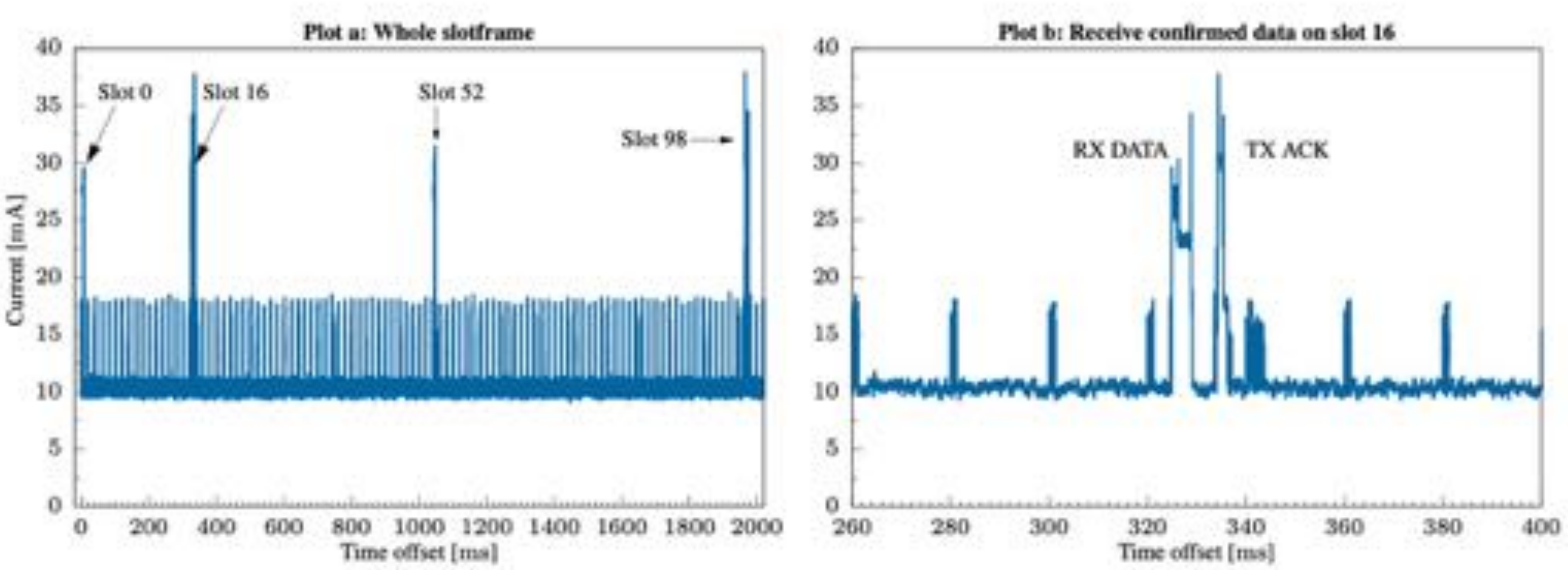
Power-consumption Model



Quantity	Action(s)	Slot offset	Energy [μJ]	Size [bytes]
$E^f_{rx\_data}$	RX DATA frame	16	178	87
$E^f_{tx\_ack}$	TX ACK frame	16	106	33
$E^f_{tx\_data}$	TX DATA frame	98	187	90
$E^f_{rx\_ack}$	RX ACK frame	98	79	33
E^f_{listen}	Idle listening	16	**138**	-
E^f_{comp}	Computation	-	628	-
E^f_{rx}	RX DATA + TX ACK	16	**284**	120
E^f_{tx}	TX DATA + RX ACK	98	**266**	123

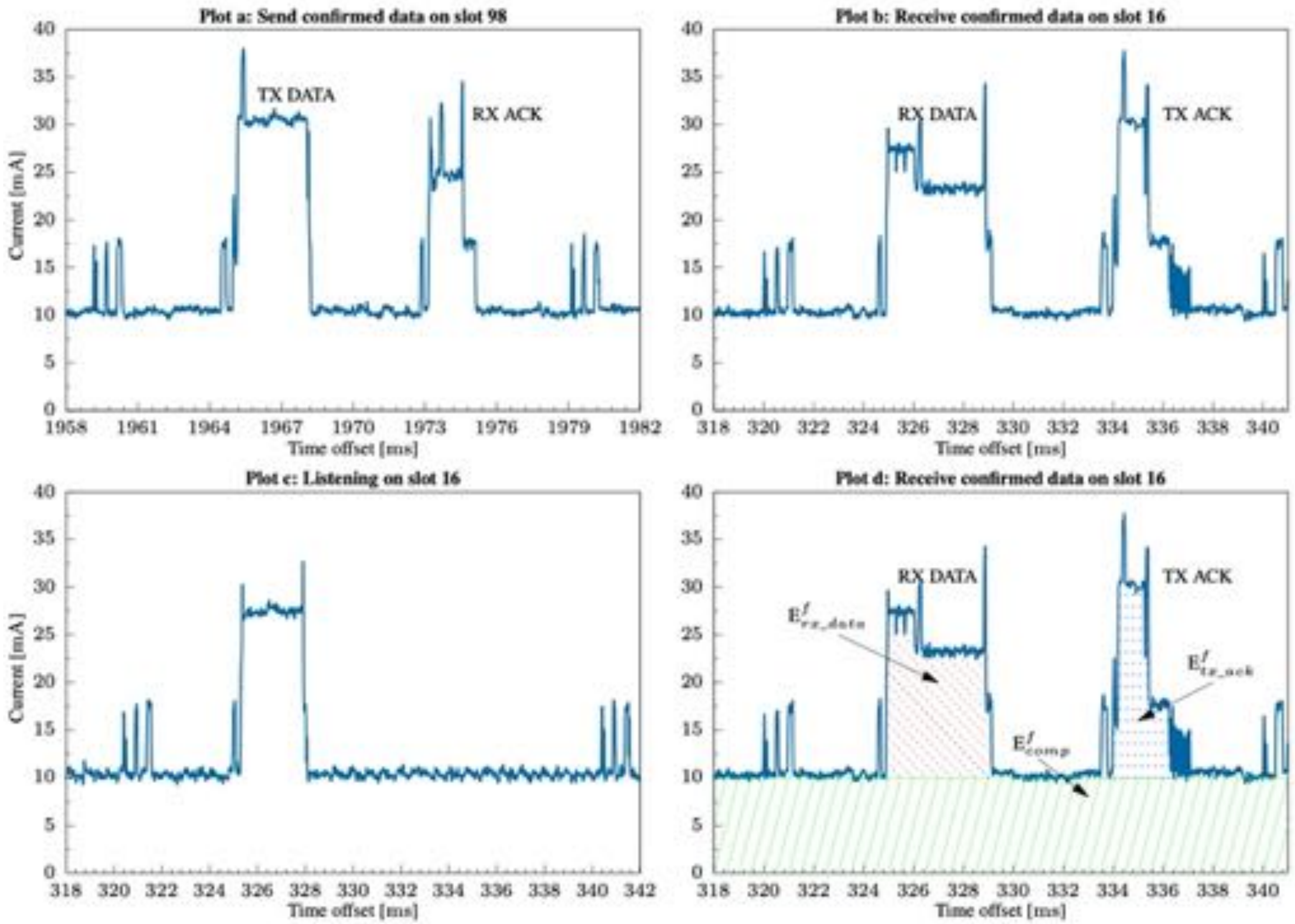
$$P = f_{tra} \cdot \left(E^f_{tx} + E^f_{rx}\right) + f_{listen} \cdot E^f_{listen},$$

Power-consumption Model



TSCH WSN

Power-consumption Model



Reliability Model

$$1 - \epsilon_{pkt} = \left(1 - \epsilon^{N_{tries}}\right)^{N_{hop}}.$$

$$n_{tra,i} = \left\lfloor \frac{d_i - d_{min}}{T_{sframe}} \right\rfloor + N_{hop},$$

$$p_{\mathrm{nr}} = (1-\epsilon)^{N_{hop}} = \frac{|\{i \mid n_{tra,i} = N_{hop}\}|}{N_{sam}},$$

$$\epsilon = 1 - \left(\frac{|\{i \mid n_{tra,i} = N_{hop}\}|}{N_{sam}}\right)^{\frac{1}{N_{hop}}}.$$

Power-consumption Model

$$E = E_{tx} + E_{rx} + E_{listen} + E_{cpu} + E_{sleep},$$

$$\begin{aligned} E_{net} &= E_{tx} + E_{rx} + E_{listen} \\ &= n_{tra} \cdot \left(E_{tx}^{f} + E_{rx}^{f}\right) + n_{listen} \cdot E_{listen}^{f}, \end{aligned}$$

$$P = f_{tra} \cdot \left(E_{tx}^{f} + E_{rx}^{f}\right) + f_{listen} \cdot E_{listen}^{f},$$

$$f_{tra} = \frac{N_{tra}}{T_{app} \cdot N_{sam}},$$

$$\begin{aligned} f_{listen} &= \frac{1}{T_{app} \cdot N_{sam}} \cdot \\ &\cdot \left(\frac{N_{hop} \cdot T_{app} \cdot N_{sam}}{T_{sframe}} - N_{tra}\right), \end{aligned}$$

$$f_{listen} = \frac{N_{hop}}{T_{sframe}} - f_{tra} = \frac{N_{hop}}{T_{slot} \cdot N_{slot}} - f_{tra}.$$

Power-consumption Model

$$N_{tra} = N_{tra}^{deliv} + N_{tra}^{lost}.$$

$$N_{tra}^{deliv} = \sum_{i=0}^{N_{sam}} n_{tra,i}.$$

$$\hat{N}_{tra}^{lost} = \hat{N}_{lost} \cdot \sum_{h=0}^{N_{hop}-1} \left[\frac{(1-\epsilon^{N_{tries}})^h - (1-\epsilon^{N_{tries}})^{h+1}}{1-(1-\epsilon^{N_{tries}})^{N_{hop}}} \right] \cdot \left(h \cdot \left(\frac{1}{1-\epsilon} - \frac{N_{tries} \cdot \epsilon^{N_{tries}}}{1-\epsilon^{N_{tries}}} \right) + N_{tries} \right)$$

Derived-quantities

$$\hat{N}_{lost} = N_{sam} \cdot \epsilon_{pkt} = N_{sam} \cdot \left(1 - (1 - \epsilon^{N_{tries}})^{N_{hop}}\right).$$

The expected number of transmission attempts performed for a packet correctly delivered on a single hop is described by a truncated geometric series

$$\frac{1}{1 - \epsilon^{N_{tries}}} \sum_{k=1}^{N_{tries}} k(1 - \epsilon)\epsilon^{k-1}.$$

$$\hat{n}_{tra} = N_{hop} \cdot \left(\frac{1}{1 - \epsilon} - \frac{N_{tries} \cdot \epsilon^{N_{tries}}}{1 - \epsilon^{N_{tries}}}\right).$$

$$\hat{f}_{tra} = \frac{\hat{n}_{tra} \cdot (N_{sam} - \hat{N}_{lost}) + \hat{N}_{tra}^{lost}}{T_{app} \cdot N_{sam}}.$$

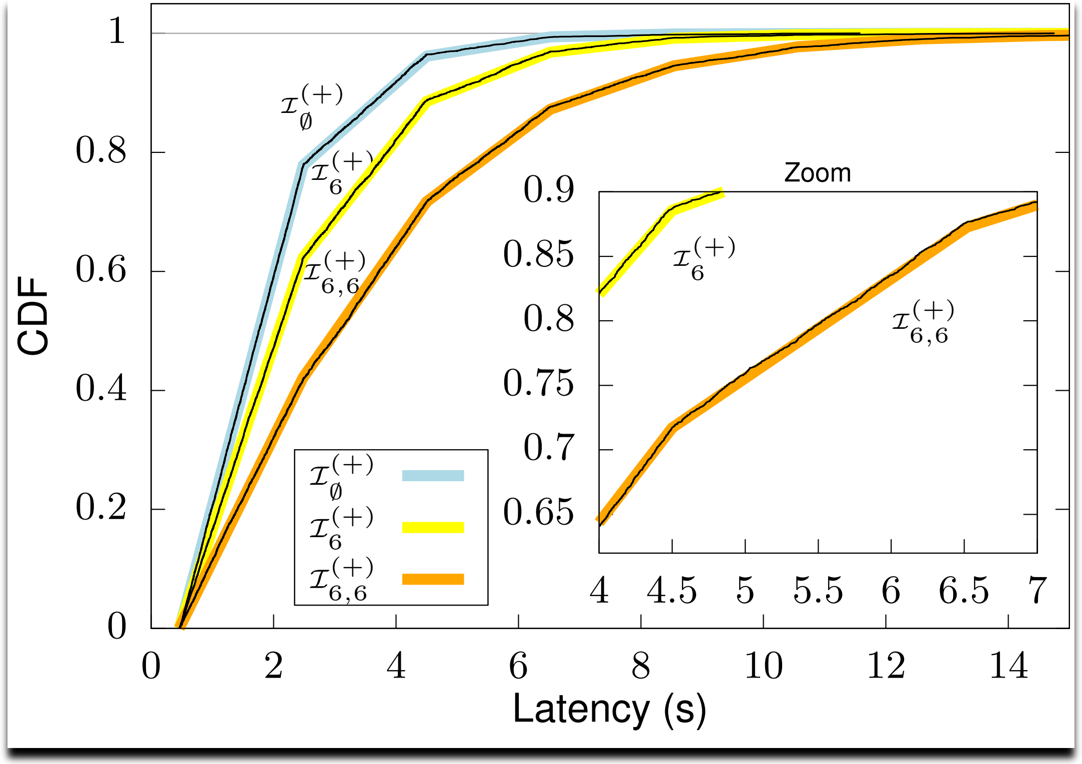
Derived-quantities

since the overall number of frames transmitted on-air for a single end-to-end packet exchange equals N_{hop} when no errors occur, and every retry uses an additional slotframe, an estimate of the average transmission latency (that, for request-response pairs, coincides with the round-trip time) can be obtained from n_tra and d_min as

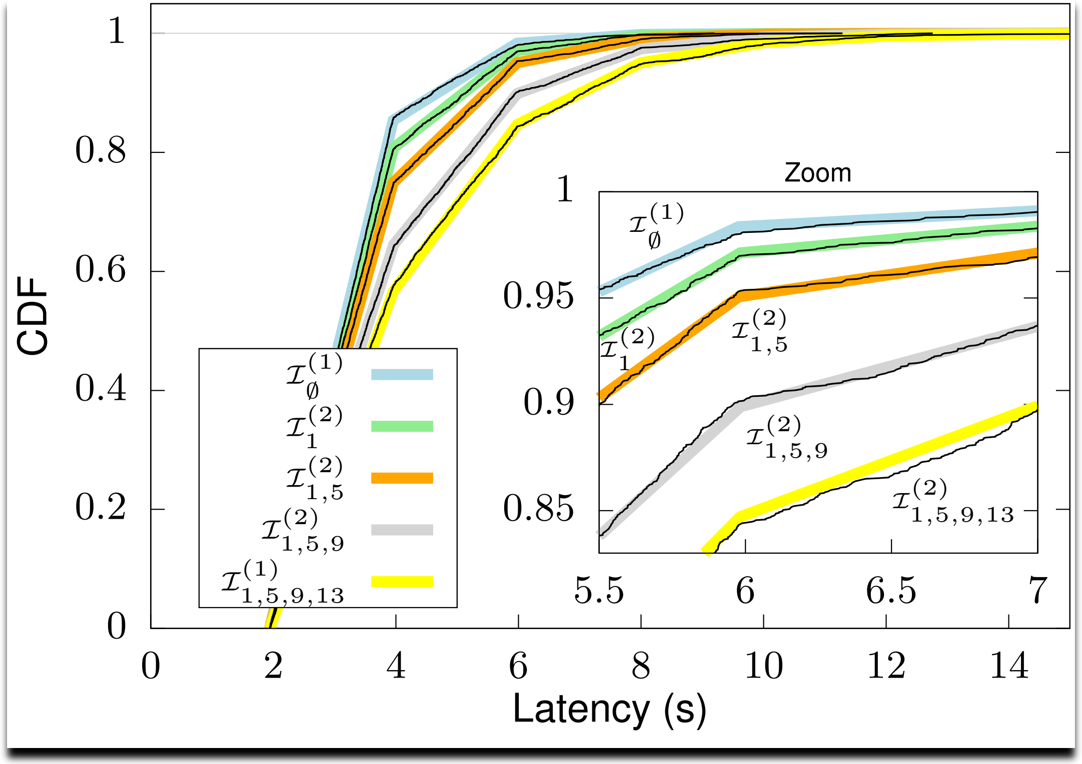
$$\hat{\mu}_d = d_{min} + \left(\frac{1}{2} + \hat{n}_{tra} - N_{hop}\right) \cdot T_{sframe}.$$

TSCH WSN

Performance analysis for Single-hop



Measured and theoretical CDFs of *d* (channel hopping disabled).



Measured and theoretical CDFs of *d* (channel hopping enabled).

Single Hop

Experimental results and estimated parameters; channel hopping disabled and enabled

Channel hopping disabled (also see plots in Fig. 5.2)

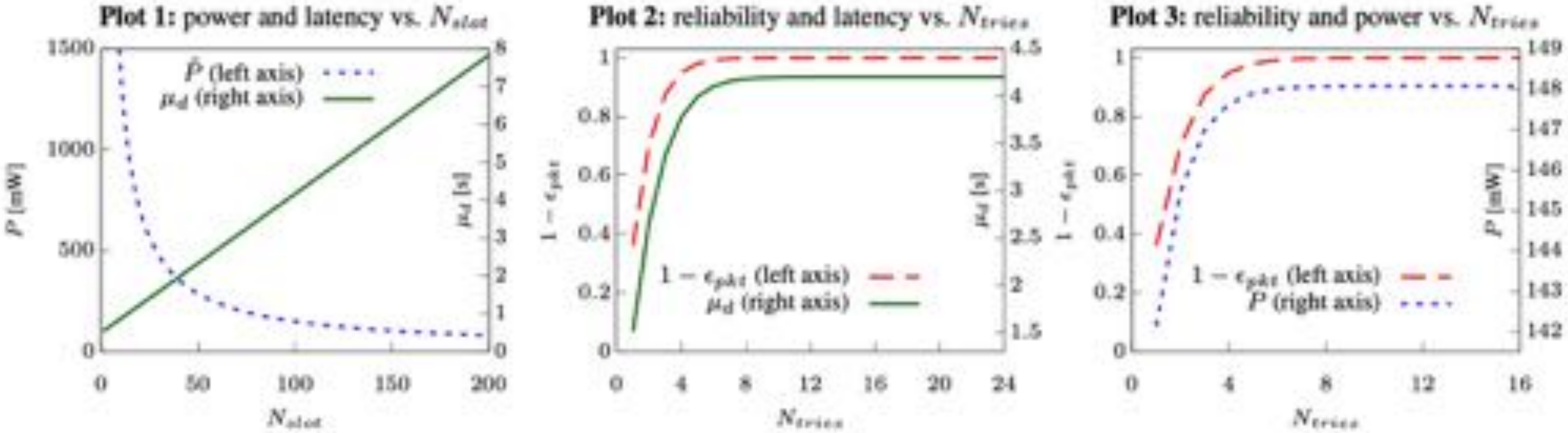
Exp.		Measured counters / ratios				Measured latencies (ms)			Estimated failure rate			Computed two-way loss ratio	
		N_L	N_0	$\hat{P}_L^T$	$\hat{P}_0^T$	d_{min}	μ_d	d_{max}	$\hat{\varepsilon}_P$	$\hat{\mu}_r$	$\hat{\varepsilon}_D$	$P_{L,P}^T$	$P_{L,D}^T$
$\mathcal{I}_{\emptyset}^{(1)}$		0	2286	0.0	0.794	466	1966.00	10723	0.109	0.121	0.108	8.03×10^{-16}	7.02×10^{-16}
$\mathcal{I}_{\emptyset}^{(2)}$		0	2189	0.0	0.760	464	2059.09	11587	0.128	0.145	0.127	1.06×10^{-14}	8.60×10^{-15}
$\mathcal{I}_{6}^{(1)}$		0	1901	0.0	0.660	460	2373.00	11872	0.188	0.224	0.183	4.69×10^{-12}	3.08×10^{-12}
$\mathcal{I}_{6}^{(2)}$		0	1682	0.0	0.584	464	2723.74	14756	0.236	0.309	0.236	1.82×10^{-10}	1.88×10^{-10}
$\mathcal{I}_{6,6}^{(1)}$		0	1092	0.0	0.379	461	3909.81	19755	0.384	0.604	0.376	4.51×10^{-07}	3.25×10^{-07}
$\mathcal{I}_{6,6}^{(2)}$		0	1318	0.0	0.458	466	3399.57	18553	0.324	0.476	0.323	2.88×10^{-08}	2.75×10^{-08}
$\mathcal{I}_{\emptyset}^{(+)}$	•	0	4475	0.0	0.777	464	2012.55	11587	0.119	0.133	0.118	3.05×10^{-15}	2.69×10^{-15}
$\mathcal{I}_{6}^{(+)}$	•	0	3583	0.0	0.622	460	2548.37	14756	0.211	0.267	0.211	3.16×10^{-11}	3.01×10^{-11}
$\mathcal{I}_{6,6}^{(+)}$	•	0	2410	0.0	0.418	461	3654.69	19755	0.353	0.541	0.351	1.17×10^{-07}	1.06×10^{-07}

Channel hopping enabled (also see plots in Fig. 5.3)

Exp.		N_L	N_0	$\hat{P}_L^T$	$\hat{P}_0^T$	d_{min}	μ_d	d_{max}	$\hat{\varepsilon}_P$	$\hat{\mu}_r$	$\hat{\varepsilon}_D$	$P_{L,P}^T$	$P_{L,D}^T$
$\mathcal{I}_{\emptyset}^{(1)}$	•	0	2465	0.0	0.856	1937	3278.97	9197	0.075	0.082	0.076	1.94×10^{-18}	2.44×10^{-18}
$\mathcal{I}_{1}^{(1)}$		0	2133	0.0	0.741	1945	3613.18	14003	0.139	0.163	0.140	4.07×10^{-14}	4.40×10^{-14}
$\mathcal{I}_{1}^{(2)}$	•	0	2320	0.0	0.806	1943	3409.05	11278	0.102	0.113	0.101	2.96×10^{-16}	2.51×10^{-16}
$\mathcal{I}_{5}^{(1)}$		0	2481	0.0	0.861	1941	3263.55	10667	0.072	0.077	0.072	1.01×10^{-18}	1.00×10^{-18}
$\mathcal{I}_{1,1}^{(1)}$		0	2109	0.0	0.732	1940	3621.55	12681	0.144	0.166	0.143	7.04×10^{-14}	5.80×10^{-14}
$\mathcal{I}_{1,5}^{(1)}$		0	1926	0.0	0.669	1940	3859.07	12332	0.182	0.225	0.184	2.96×10^{-12}	3.36×10^{-12}
$\mathcal{I}_{1,5}^{(2)}$	•	0	2149	0.0	0.746	1938	3575.46	11289	0.136	0.155	0.134	2.80×10^{-14}	2.28×10^{-14}
$\mathcal{I}_{1,5,9}^{(1)}$		0	1524	0.0	0.529	1940	4438.65	16942	0.273	0.368	0.269	1.86×10^{-09}	1.53×10^{-09}
$\mathcal{I}_{1,5,9}^{(2)}$	•	0	1848	0.0	0.642	1944	3944.73	12761	0.199	0.245	0.197	1.21×10^{-11}	1.02×10^{-11}
$\mathcal{I}_{1,5,13}^{(1)}$		0	1952	0.0	0.678	1941	3810.58	15999	0.177	0.213	0.175	1.81×10^{-12}	1.61×10^{-12}
$\mathcal{I}_{1,5,9,13}^{(1)}$	•	0	1659	0.0	0.576	1942	4277.65	17288	0.241	0.328	0.247	2.59×10^{-10}	3.85×10^{-10}
$\mathcal{I}_{1,5,9,13}^{(2)}$		0	1768	0.0	0.614	1943	4076.80	13649	0.216	0.278	0.218	4.66×10^{-11}	5.06×10^{-11}
$\mathcal{I}_{1,1,5,5}^{(1)}$		0	1638	0.0	0.569	1945	4316.97	16035	0.246	0.337	0.252	3.56×10^{-10}	5.33×10^{-10}

Practical application contexts

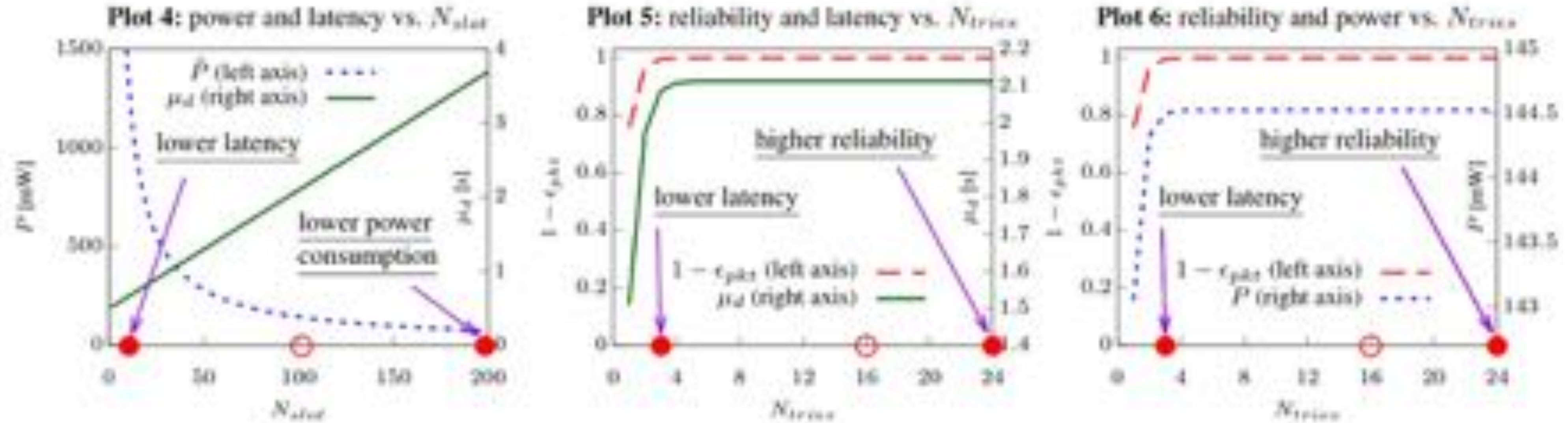
Leveraging the mathematical model



Influence of N_{slot} and N_{tries} on reliability, power consumption, and latency, evaluated using the proposed network model (ϵ =0.4, N_{tries} =16 for Plot 1, N_{slot} =101 for Plot 2 and Plot 3).

Practical application contexts

Evaluation of relevant configurations



Influence of N_{slot} and N_{tries} on reliability, power consumption, and latency, evaluated using the proposed network model (ϵ =0.13, N_{tries} =16 for Plot 4, N_{slot} =101 for Plot 5 and Plot 6). Effects of moving working points—marked with solid red circles (•)—away from the default configuration—marked with emptyred circles (◦)—are suitably labelled.

TSCH predictor

Algorithm 1: Simulation logic at the *TSCH event*

$FDP \leftarrow (1 - \epsilon)$
$ACK \leftarrow (1 - \epsilon_{ACK})$
while TRUE **do**
  if random.uniform(0,1) $\leq FDP$ **then**
    DATA frame arrived in subsequent node
    if random.uniform(0,1) $\leq ACK$ **then**
      ACK frame arrived to source node
    else
      ACK frame did not arrive at source node
    end if
  else
    ACK frame sent but did not arrive at the following node
  end if
end while

TSCH predictor web Interfaces