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FACULTY OF ENGINEERING
AND ARCHITECTURE

DEPARTMENT INTEC
RESEARCH GROUP IDLAB

IMPROVING EFFICIENCY, USABILITY AND SCALABILITY IN A SECURE, RESOURCE-CONSTRAINED WEB OF THINGS

Floris Van den Abeele

28/09/2017

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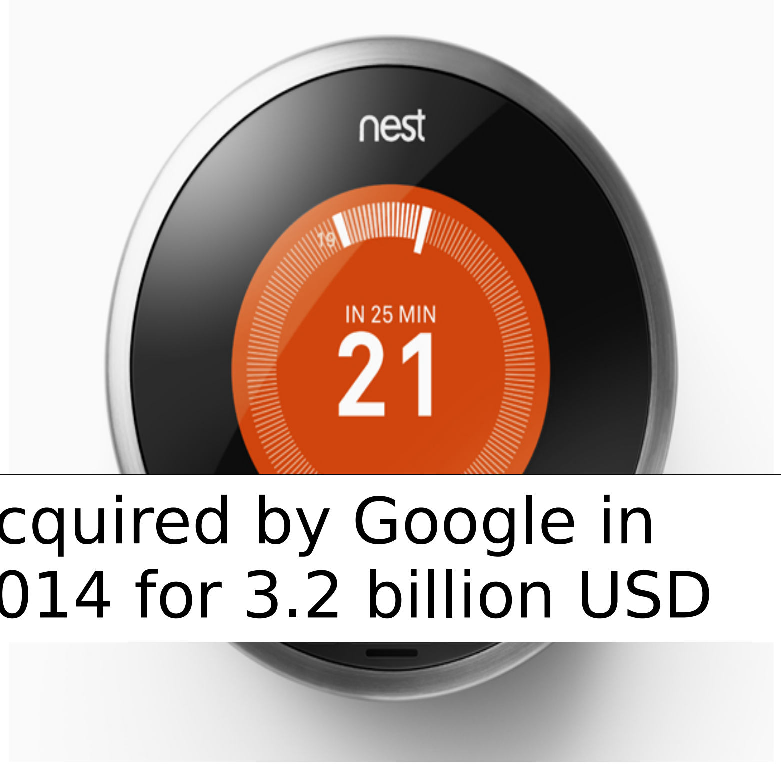
1. INTRODUCTION

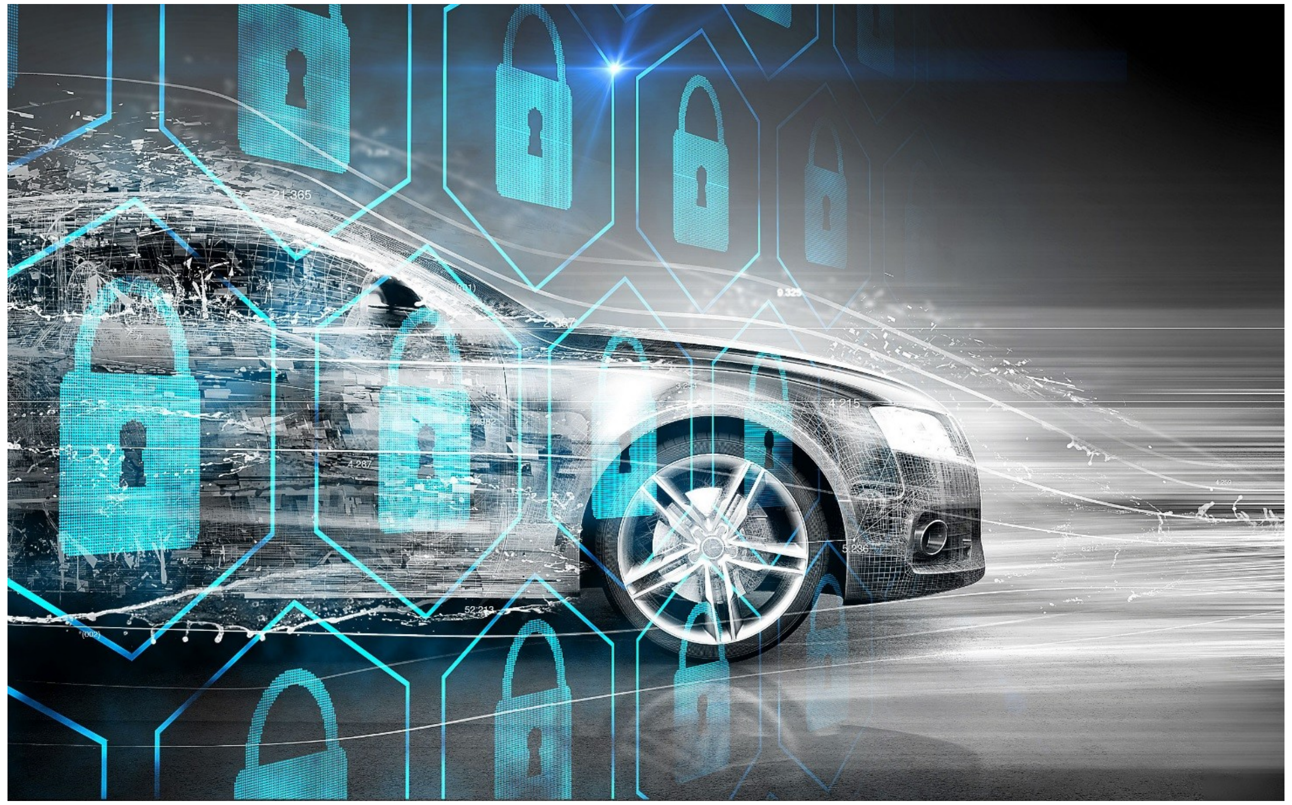
INTERNET OF THINGS: HOME AUTOMATION

INTERNET OF THINGS: HOME AUTOMATION



Acquired by Google in 2014 for 3.2 billion USD

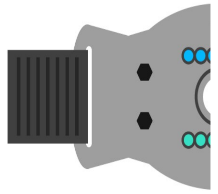
INTERNET OF THINGS: TRANSPORT

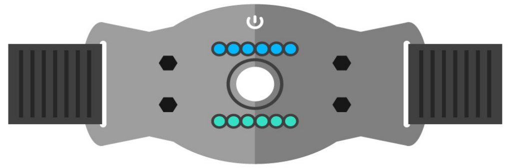


INTERNET OF THINGS: UTILITIES

Flanders starts the roll out of digital energy meters in 2019.

INTERNET OF THINGS: EHEALTH



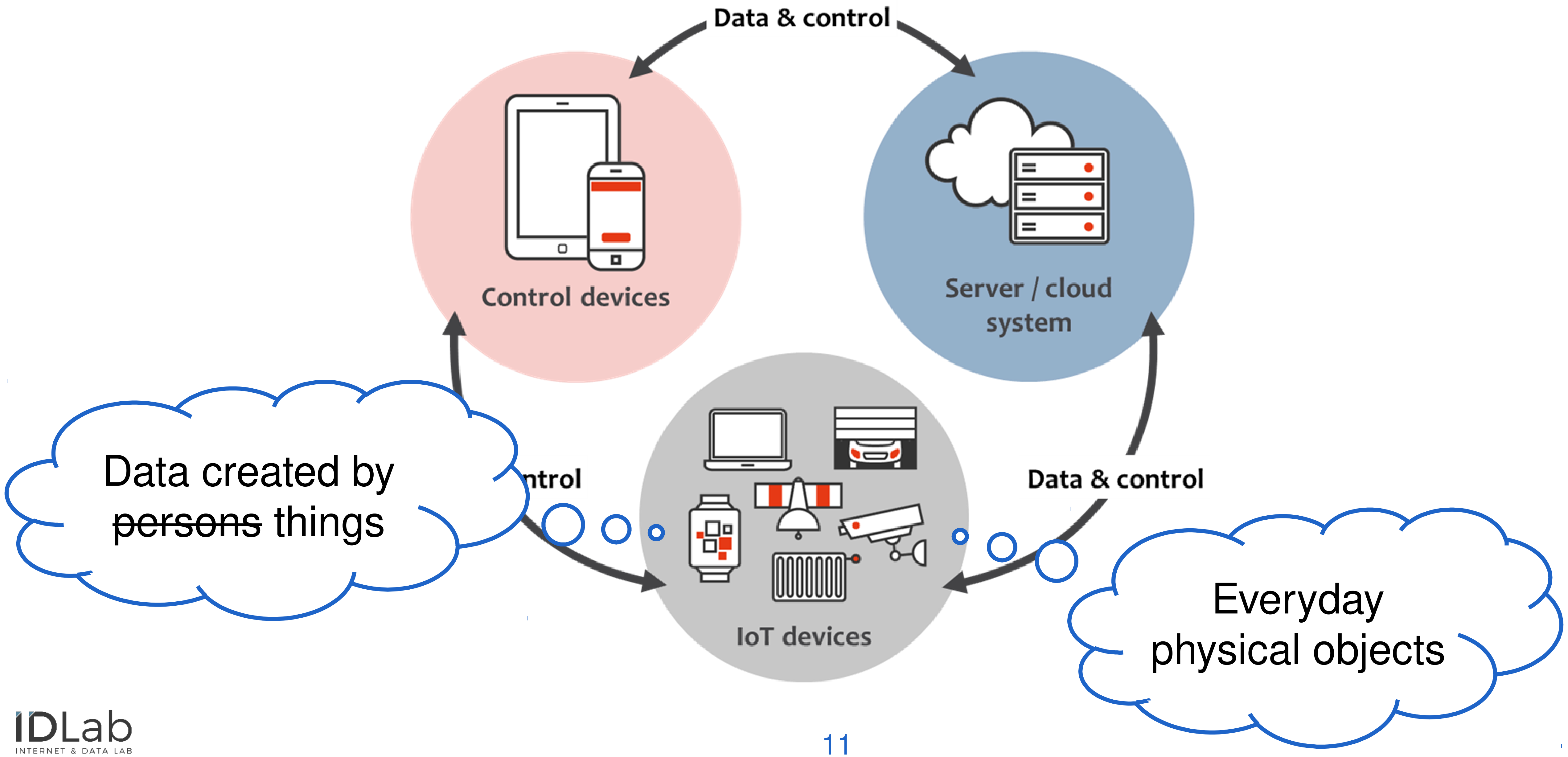


INTERNET OF THINGS: EHEALTH

Real-time remote health monitoring

INTERNET OF THINGS

"*The Internet of Things is the combination of sensors, actuators, distributed computing power, wireless communication on the hardware side and applications and big data/analytics on the software side.*" – Morgan Stanley



INTERNET OF THINGS

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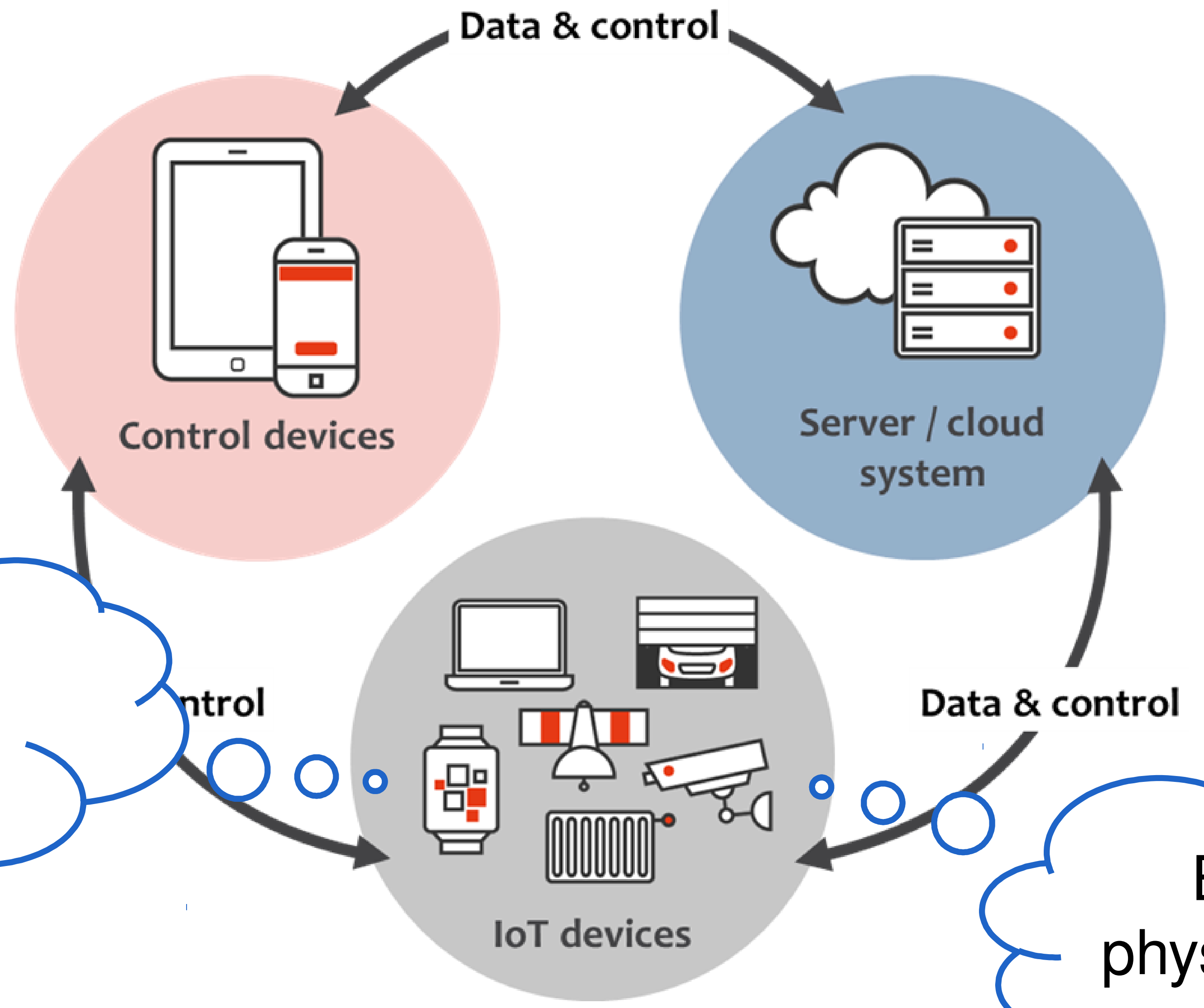
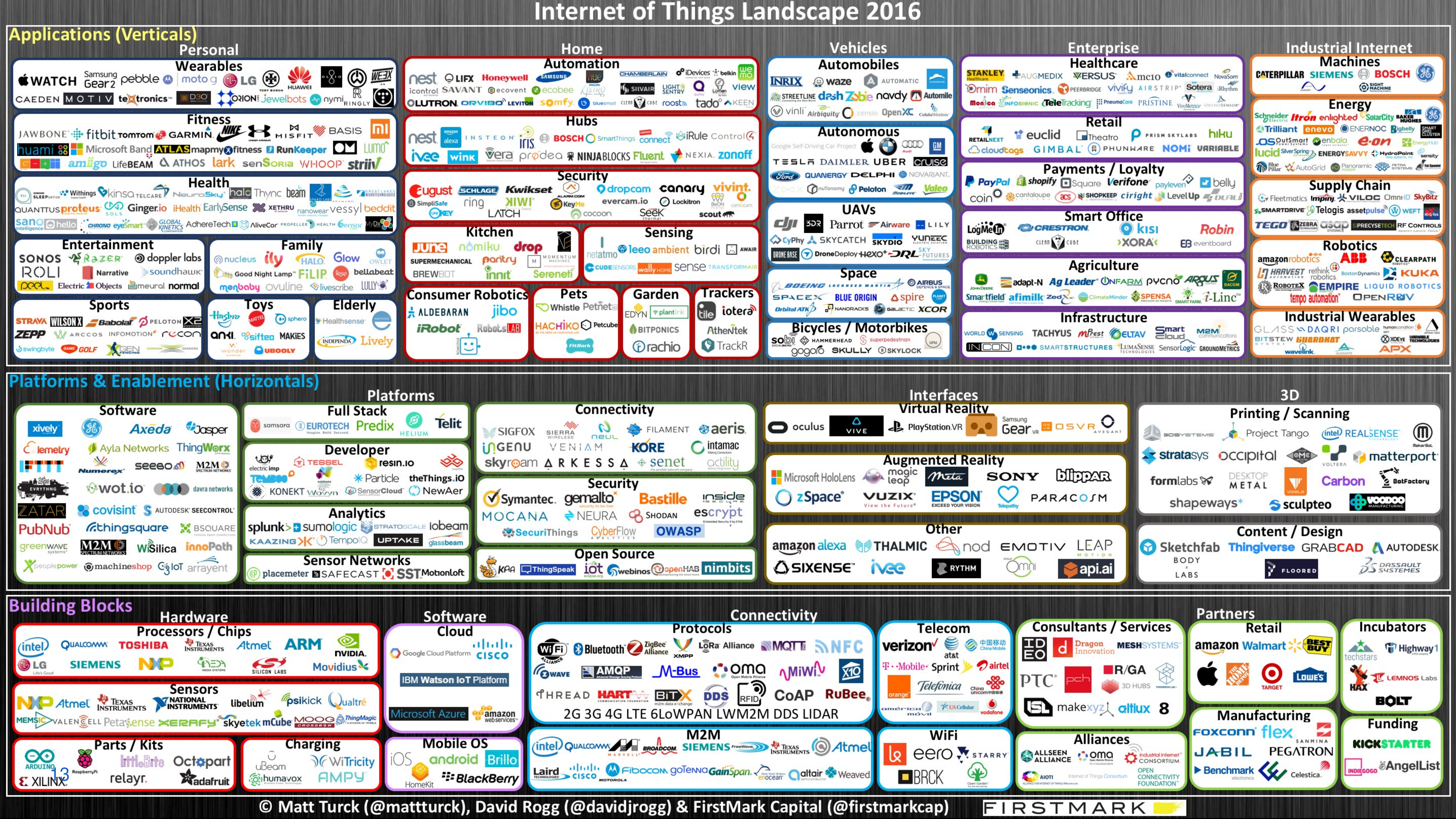


Data created by ~~persons~~ things

Everyday physical objects

50 billion Internet-connected devices by 2020 (Cisco)

21 billion IoT units by 2020 (Gartner)



Internet of Things Landscape 2016
Applications (Verticals)
Personal
Wearables
WATCH Samsung Gear2 pebble moto LG TORY BURCH HUAWEI WEEX CAEDEN MOTIV textronics D3O ORION Jewelbots nymi RINGLY
Fitness
JAWBONE fitbit TOMTOM GARMIN NIKE UNDER ARMOUR MISFIT BASIS mi huami Microsoft Band ATLAS mapmyfitness RunKeeper LUMO amiigo LifeBEAM ATHOS lark senSoria WHOOP striiv
Health
Withings kinsa TELCARE NeuroSky halo Thync beam QUANTTUS proteus SOLS Ginger.io iHealth EarlySense XETHRU nanowear vessyl beddit sano hello CHRONO eyeSmart GLOBAL KINETICS AdhereTech AliveCor PROPELLER HEALTH Gensor
Entertainment
SONOS RAZER doppler labs ROLI Narrative soundhawk peel Electric Objects meural normal
Family
nucleus ily HALO Glow OWLET Good Night Lamp FiLIP bellabeat monbaby ovuline livescribe LILLY
Sports
STRAVA WILSON X Babolat PELOTON ZEPP ARCCOS INFOMOTION recon swingbyte GAME GOLF
Toys
Hasbro sphero anki sifteo MAKIES wonder UBOOLY
Elderly
Healthsense INDEPENDA Lively
Home
Automation
nest LIFX Honeywell SAMSUNG hue CHAMBERLAIN iDevices belkin wemo icontrol SAVANT ecovent ecobee ASTRO SILVAIR LIGHT SENTRY Lumen view LUTRON ORVIBO LEVITON somfy bluesmart CUBE roost tado KEEN
Hubs
nest amazon alexa INSTEON iris BOSCH SmartThings connect iRule Control4 ivee wink Vera prodea NINJABLOCKS Fluent NEXIA zonoff
Security
august SCHLAGE Kwikset ALARM.COM dropcam canary vivint SimpliSafe ring KIWI KeyMe evercam.io Lockitron UniKey LATCH cocoon Seek scout
Kitchen
JUNE nomiku drop SUPERMECHANICAL pantry BREWBOT innit Sereneti
Sensing
netatmo leeo ambient birdi AWAIR CUBESENSORS wally HOME sense TRANSFORMAIR
Consumer Robotics
ALDEBARAN jibo iRobot RobotsLAB
Pets
Whistle Petnet HACHIKO Petcube FitBark
Garden
EDYN plantlink BITPONICS rachio
Trackers
tile iotera AthenTek TrackR
Vehicles
Automobiles
INRIX waze AUTOMATIC STREETLINE dash Zubie navdy Automile vinli Airbiquity OpenXC
Autonomous
Google Self-Driving Car Project Audi GM TESLA DAIMLER UBER cruise Ford QUANERGY DELPHI NOVARIANT nuTonomy Peloton Mobileye Valeo
UAVs
dji 3DR Parrot Airware LILY CyPhy SKYCATCH SKYDIO YUNEEC DRONE BASE DroneDeploy HEXO+ DRL SKY FUTURES
Space
BOEING LOCKHEED MARTIN AIRBUS SPACEX BLUE ORIGIN spire PLANET Orbital ATK NANORACKS GALACTIC XCOR
Bicycles / Motorbikes
sobi HAMMERHEAD superpedestrian unu gogoro SKULLY SKYLOCK
Enterprise
Healthcare
STANLEY Healthcare AUGMEDIX VERSUS mc10 vitalconnect NovaSom mim Senseonics PEERBRIDGE vivify AIRSTRIP Sotera iRhythm Monica INFOBIONIC TeleTracking PneumaCore PRISTINE VivoMetrics ORTHOSENSOR
Retail
RETAILNEXT euclid Theatro PRISM SKYLABS hiku cloudtags GIMBAL PHUNWARE NOMI VARIABLE
Payments / Loyalty
PayPal shopify Square Verifone payleven belly coin cantaloupe acs SHOPKEEP ciright LevelUp DUAL
Smart Office
LogMeIn CRESTRON kisi Robin BUILDING ROBOTICS CUBE XORA eventboard
Agriculture
JOHN DEERE adapt-N Ag Leader ONFARM pycno ARGUS DACOM Smartfield afimilk Zedx ClimateMinder SPENSA SMART FARM i-Linc
Infrastructure
WORLD SENSING TACHYUS mPest DELTAV Smart Cloud M2M communications INCON SMARTSTRUCTURES LUMASENSE SensorLogic GROUNDMETRICS
Industrial Internet
Machines
CATERPILLAR SIEMENS BOSCH GE SIGHT MACHINE
Energy
Schneider Electric Itron enlighted SolarCity BAKER HUGHES Trilliant enevo ENERNOC Bigbelly SMART GRID CLUSTER OutSmart enbala e-on EnergyHub lucid Silver Spring ENERGYSAVVY HydroPoint sensity Blue Pillar AutoGrid Panoramic
Supply Chain
Fleetmatics Impinj VILOC OmniID SkyBitz SMARTDRIVE Telogis assetpulse WEFT TEGO ZEBRA asap PRECYSETECH RF CONTROLS
Robotics
amazon robotics ABB CLEARPATH HARVEST rethink robotics BostonDynamics KUKA ROBOTEX EMPIRE LIQUID ROBOTICS tempo automation OPENROV
Industrial Wearables
GLASS DAQRI parsable XOEYE BITSTEW GUARDHAT wavelink APX
Platforms & Enablement (Horizontals)
Platforms
Software
xively GE Axeda Jasper lemetry Ayla Networks ThingWorx IFTTT Numerex seeed M2M EVRYTHNG wot.io davra networks ZATAR covisint AUTODESK SEECONTROL PubNub thingsquare BSQUARE greenwave systems M2M SPECTRUM NETWORKS WiSilica innoPath peoplepower machineshop IoT arrayent
Full Stack
samsara EUROTECH Predix HELIUM Telit
Developer
electric imp TESSEL resin.io Temboo KONEKT estimote Particle theThings.iO wovyn SensorCloud NewAer
Analytics
splunk sumologic STRATOSCALE iobeam KAAZING TempoIQ UPTAKE glassbeam
Sensor Networks
placemeter SAFECAST SST MotionLoft
Connectivity
SIGFOX SIERRA WIRELESS neul FILAMENT aeris INGENU VENIAM KORE intamac skyroam ARKESSA senet actility
Security
Symantec gemalto Bastille inside escrypt MOCANA NEURA SHODAN SecuriThings CyberFlow OWASP
Open Source
KAA ThingSpeak iot eclipse webinos openHAB nimbits
Interfaces
Virtual Reality
oculus VIVE PlayStation VR Samsung Gear VR OSVR AVEGANT
Augmented Reality
Microsoft HoloLens magic leap Meta SONY blippar zSpace VUZIX EPSON Telepathy PARACOSM
Other
amazon alexa THALMIC nod EMOTIV LEAP MOTION SIXENSE ivee RYTHM Omni api.ai
3D
Printing / Scanning
3DSYSTEMS Project Tango intel REALSENSE MakerBot stratasys occipital OMC VOLTERA matterport formlabs DESKTOP METAL VOXEL8 Carbon BotFactory shapeways sculpteo VOODOO MANUFACTURING
Content / Design
Sketchfab Thingiverse GRABCAD AUTODESK BODY LABS FLOORED DASSAULT SYSTEMES
Building Blocks
Hardware
Processors / Chips
intel QUALCOMM TOSHIBA TEXAS INSTRUMENTS Atmel ARM NVIDIA LG SIEMENS NXP INEDA SYSTEMS SILICON LABS Movidius
Sensors
NXP Atmel TEXAS INSTRUMENTS NATIONAL INSTRUMENTS libelium psikick Qualtré MEMSIC VALENCELL Petasense XERAFY skyetek mCube MOOG ThingMagic
Parts / Kits
ARDUINO RaspberryPi littleBits Octopart XILINX relayr adafruit
Charging
uBeam WiTricity humavox AMPY
Software
Cloud
Google Cloud Platform CISCO IBM Watson IoT Platform Microsoft Azure amazon web services
Mobile OS
iOS android Brillo HomeKit BlackBerry
Connectivity
Protocols
WiFi ALLIANCE Bluetooth ZigBee Alliance XMPP LoRa Alliance MQTT NFC ZWAVE AMQP M-Bus oma MiWi X10 THREAD HART BiTX DDS RFID CoAP RuBee
2G 3G 4G LTE 6LoWPAN LWM2M DDS LIDAR
Telecom
verizon at&t 中国移动 China Mobile T-Mobile Sprint airtel orange Telefonica China unicom América Movil US Cellular vodafone
M2M
intel QUALCOMM MARVELL BROADCOM SIEMENS TEXAS INSTRUMENTS Atmel Laird CISCO MOTOROLA Fibocom goTenna GainSpan enocean altair Weaved
WiFi
eero STARRY BRCK Open Garden
Partners
Consultants / Services
IDEO Dragon Innovation MESHSYSTEMS PTC pch R/GA 3D HUBS ISL makexyz altiux 8
Alliances
ALLSEEN ALLIANCE oma industrial internet CONSORTIUM AIOTI Internet of Things Consortium OPEN CONNECTIVITY FOUNDATION
Retail
amazon Walmart BEST BUY TARGET LOWE'S
Manufacturing
FOXCONN flex SANMINA JABIL PEGATRON Benchmark Celestica
Incubators
techstars Highway1 HAX LEMNOS Labs BOLT
Funding
KICKSTARTER INDIEGOGO AngelList
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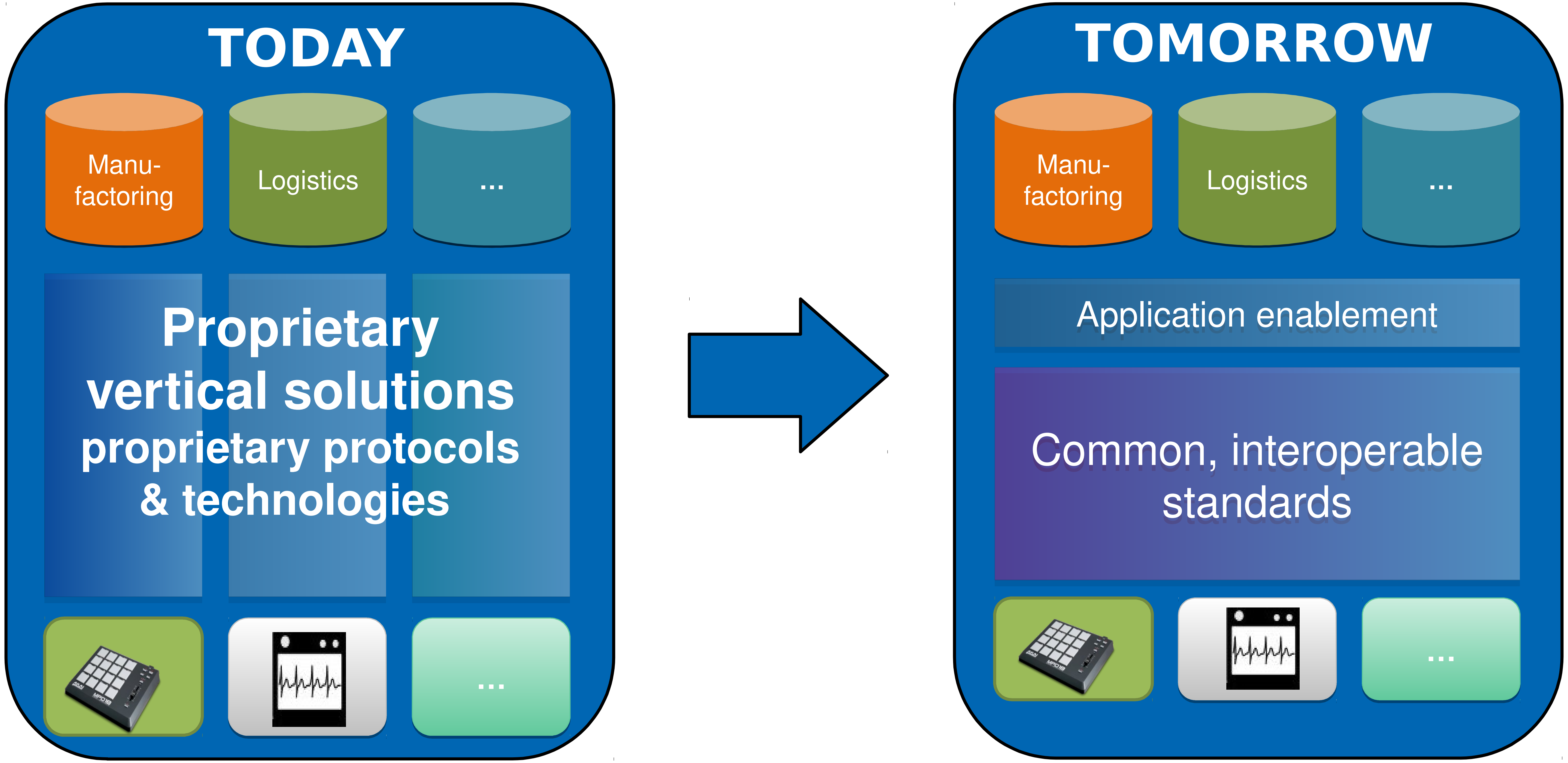
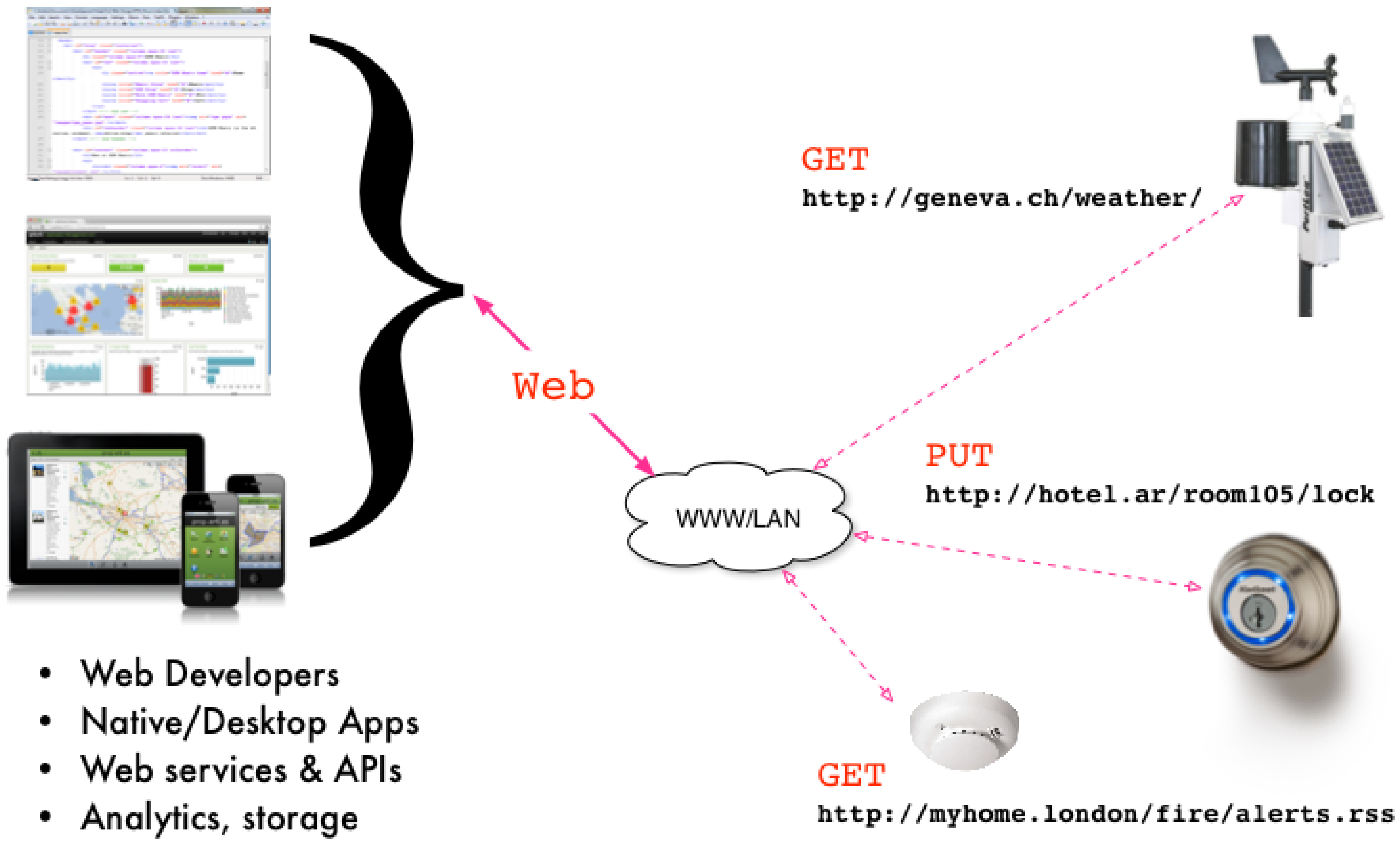
BREAKING THE VERTICAL SILOS IN IOT

NEED FOR STANDARDS ON TOP OF CONNECTIVITY SOLUTIONS



WEB OF THINGS?

- “The **Web of Things** is a refinement of the Internet of Things by integrating smart things not only into the Internet, but into the Web Architecture.”
- Designed for interoperability <-> **Intranet** of Things



- Web Developers
- Native/Desktop Apps
- Web services & APIs
- Analytics, storage

Source: Building the Web of Things: book.webofthings.io

Improving **Efficiency**, **Usability** and **Scalability** in a **Secure**, Resource-Constrained Web of Things

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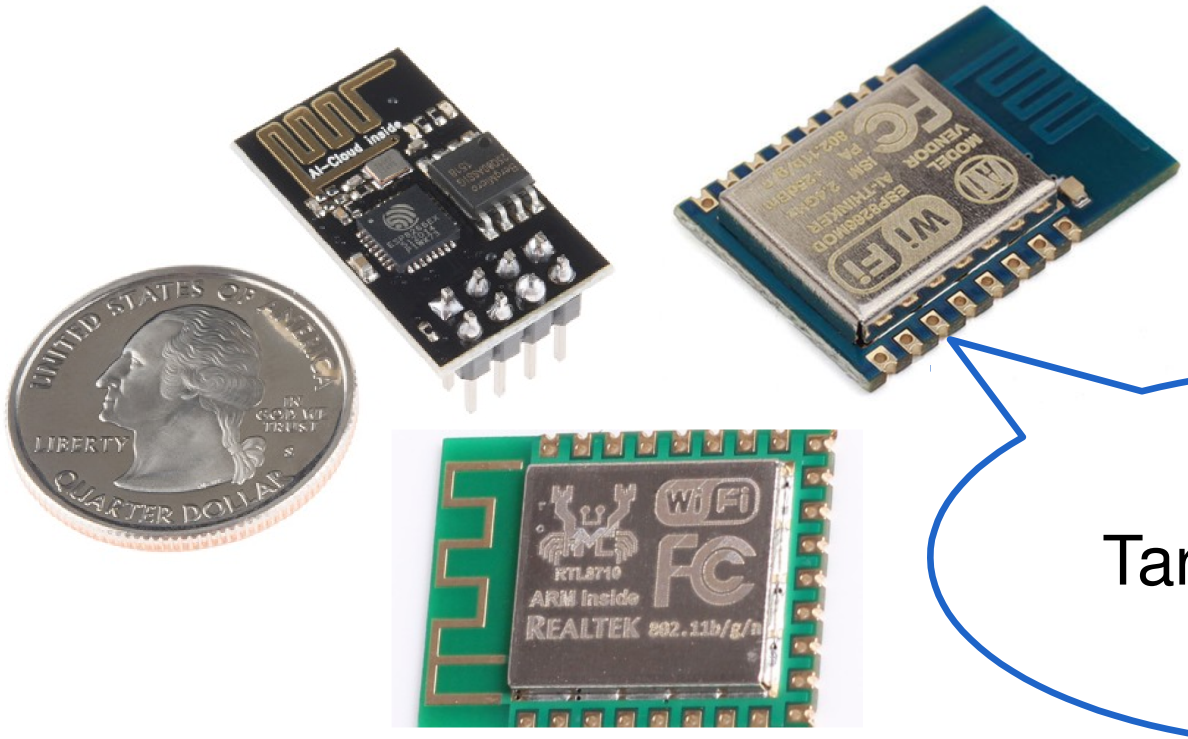
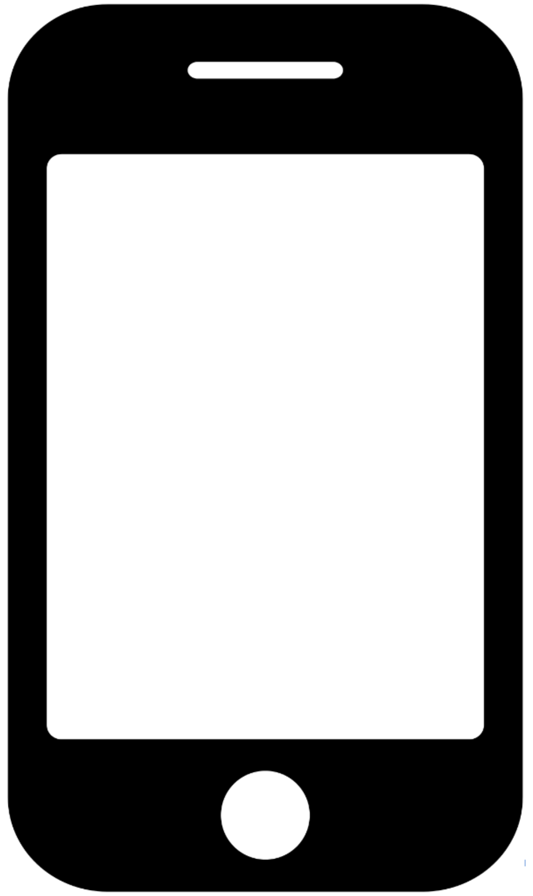
CONSTRAINED DEVICES

Tiny, resource-constrained devices: networked embedded systems



Target < 1 USD



Target hundreds of USD

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CONSTRAINED DEVICES

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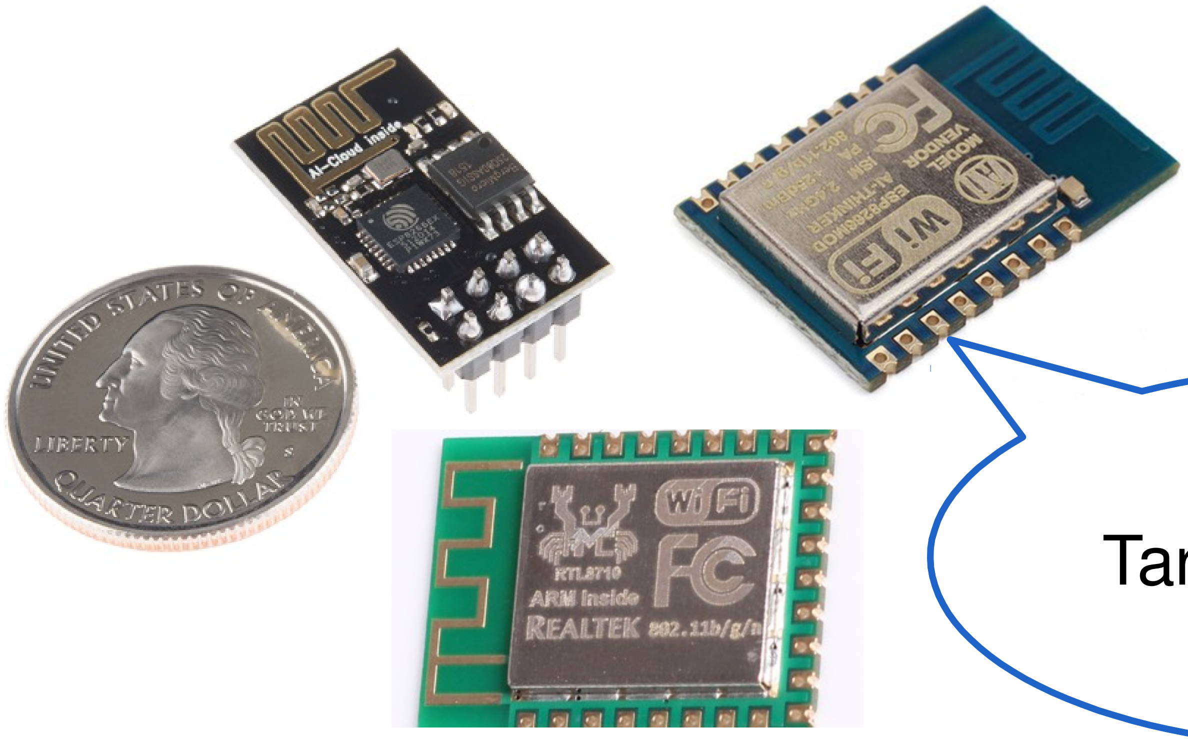

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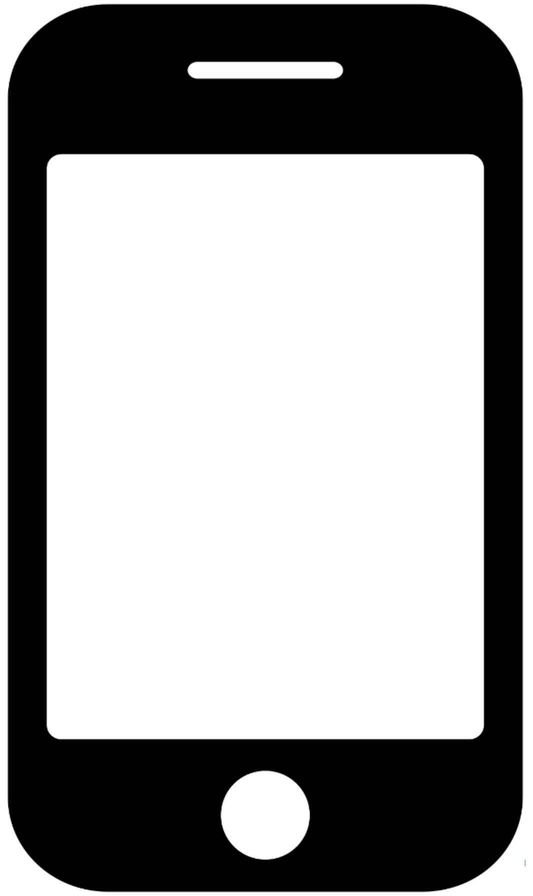


Target hundreds of USD

Class 1 devices:
~100KB ROM
~10KB RAM
Low power, low cost
Battery lifetime: years

Smart phones:
~100GB ROM
~4GB RAM
Expensive
Battery lifetime: 1 day

RESOURCE-CONSTRAINED WEB OF THINGS

RESTful embedded web services:

Minimal memory footprint

Compact encodings & headers

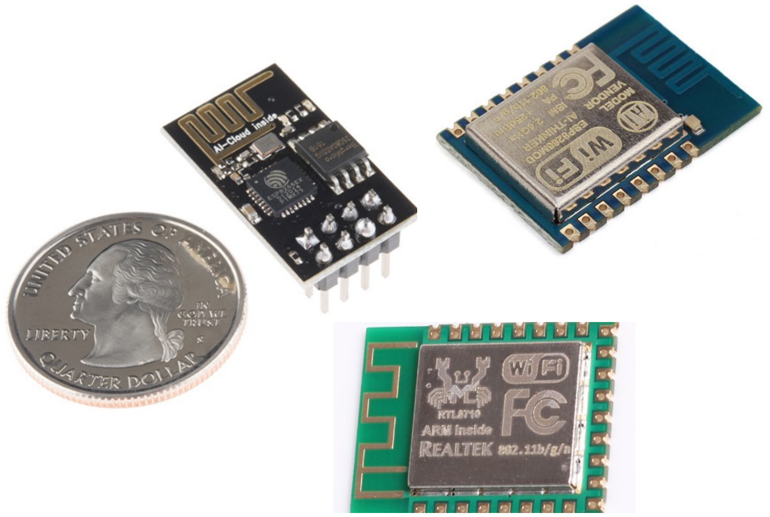
Minimize communication

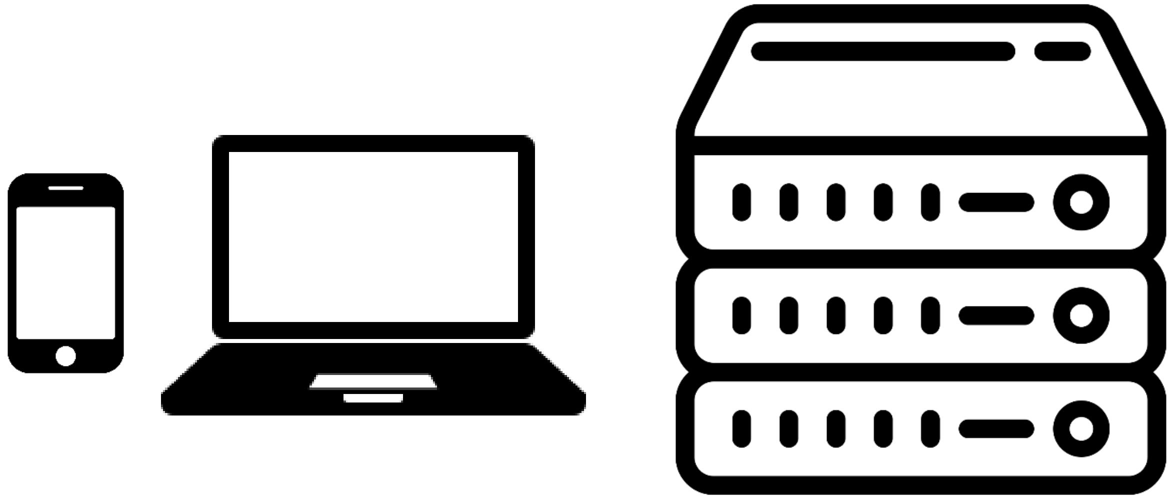
RESTful web services:

Memory footprint less important

Plain-text encodings & headers

Always-on communication





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RESOURCE-CONSTRAINED WEB OF THINGS

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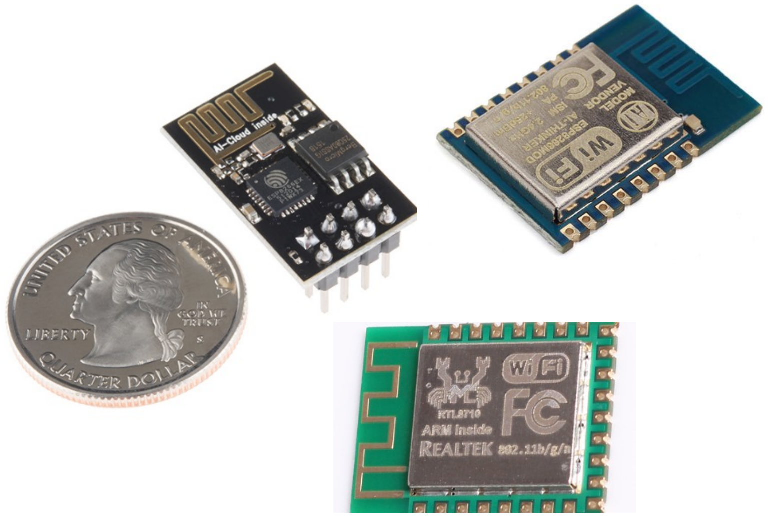
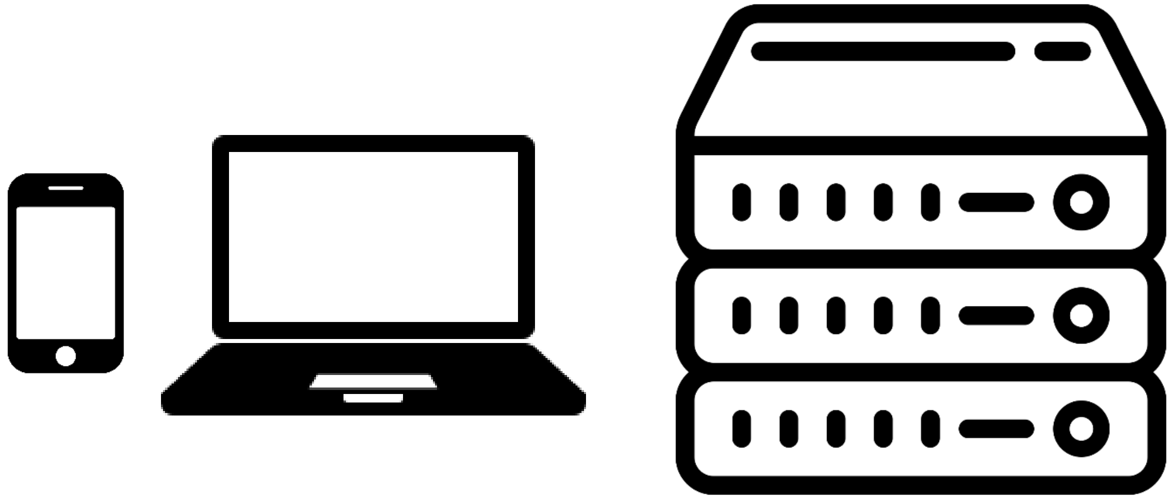
Always-on communication

New technologies





6lo/IPv6/UDP-DTLS/CoAP/CBOR

IPv6/TCP-TLS/HTTP/JSON

Multi hop wireless networks, LPWANs

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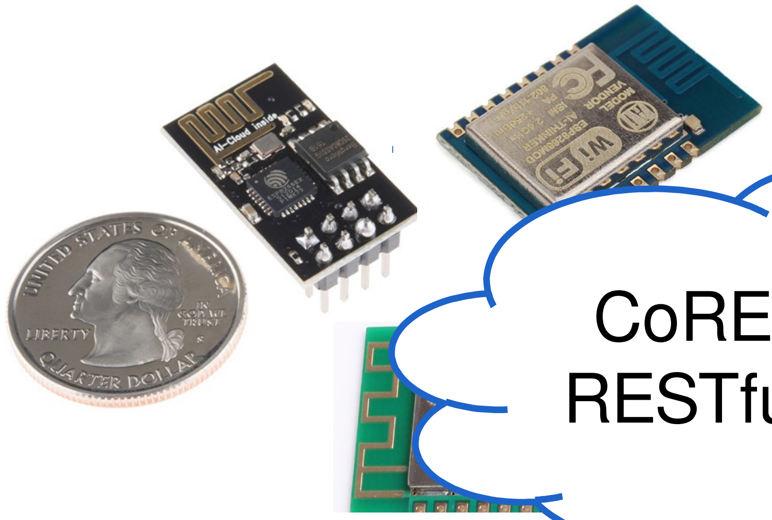
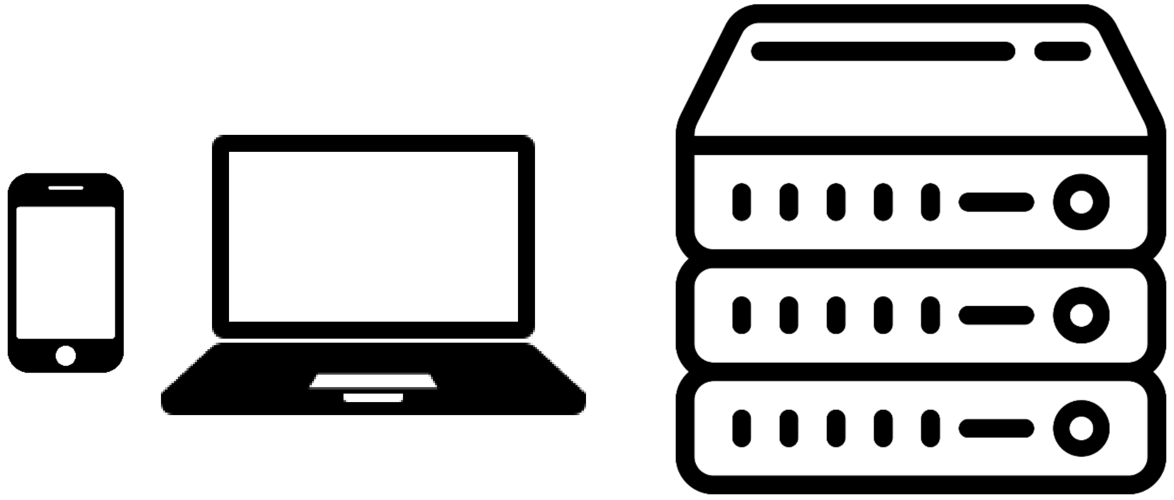


CoRE: Constrained RESTful Enviroments

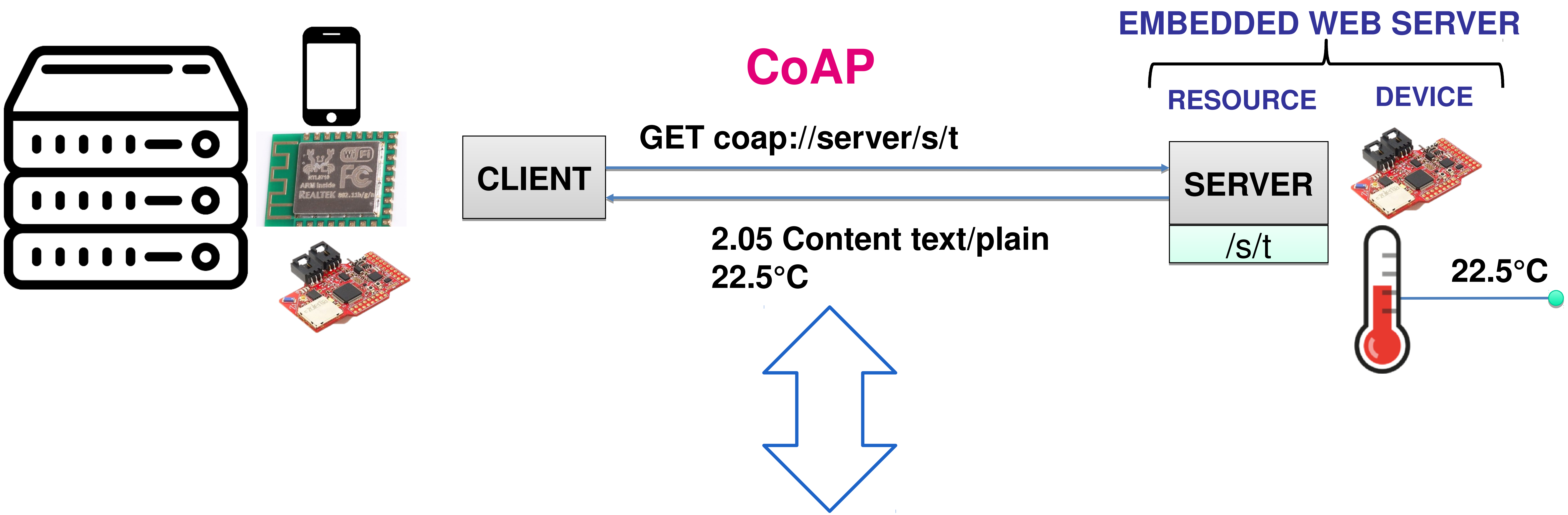


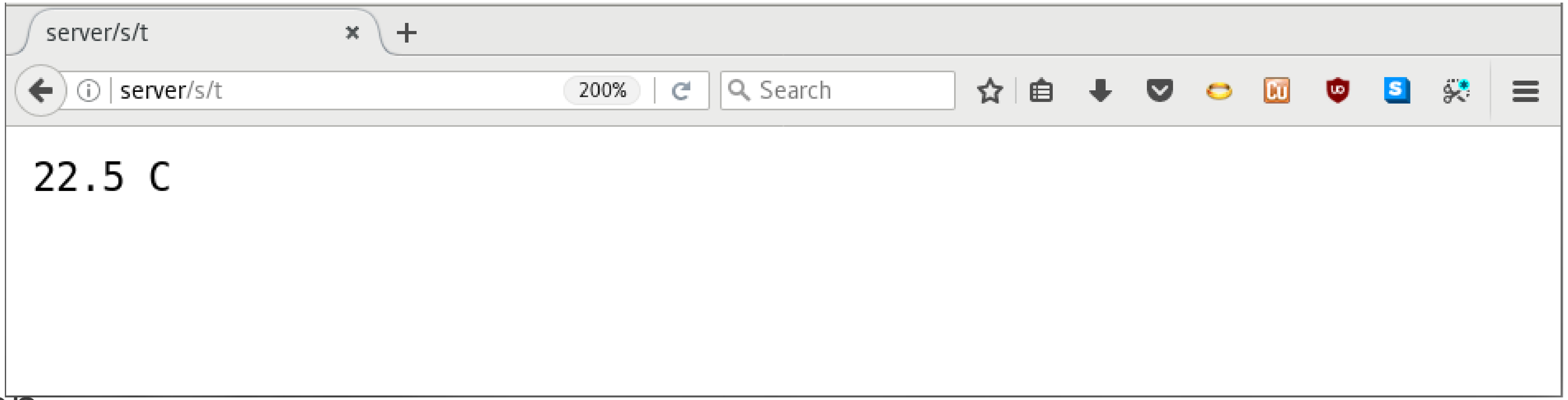
6lo/IPv6/UDP-DTLS/CoAP/CBOR

IPv6/TCP-TLS/HTTP/JSON

Multi hop wireless networks, LPWANs

RESOURCE-CONSTRAINED WEB OF THINGS: EXAMPLE





Improving **Efficiency**, **Usability** and **Scalability** in a Secure, Resource-Constrained Web of Things

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2. RESEARCH

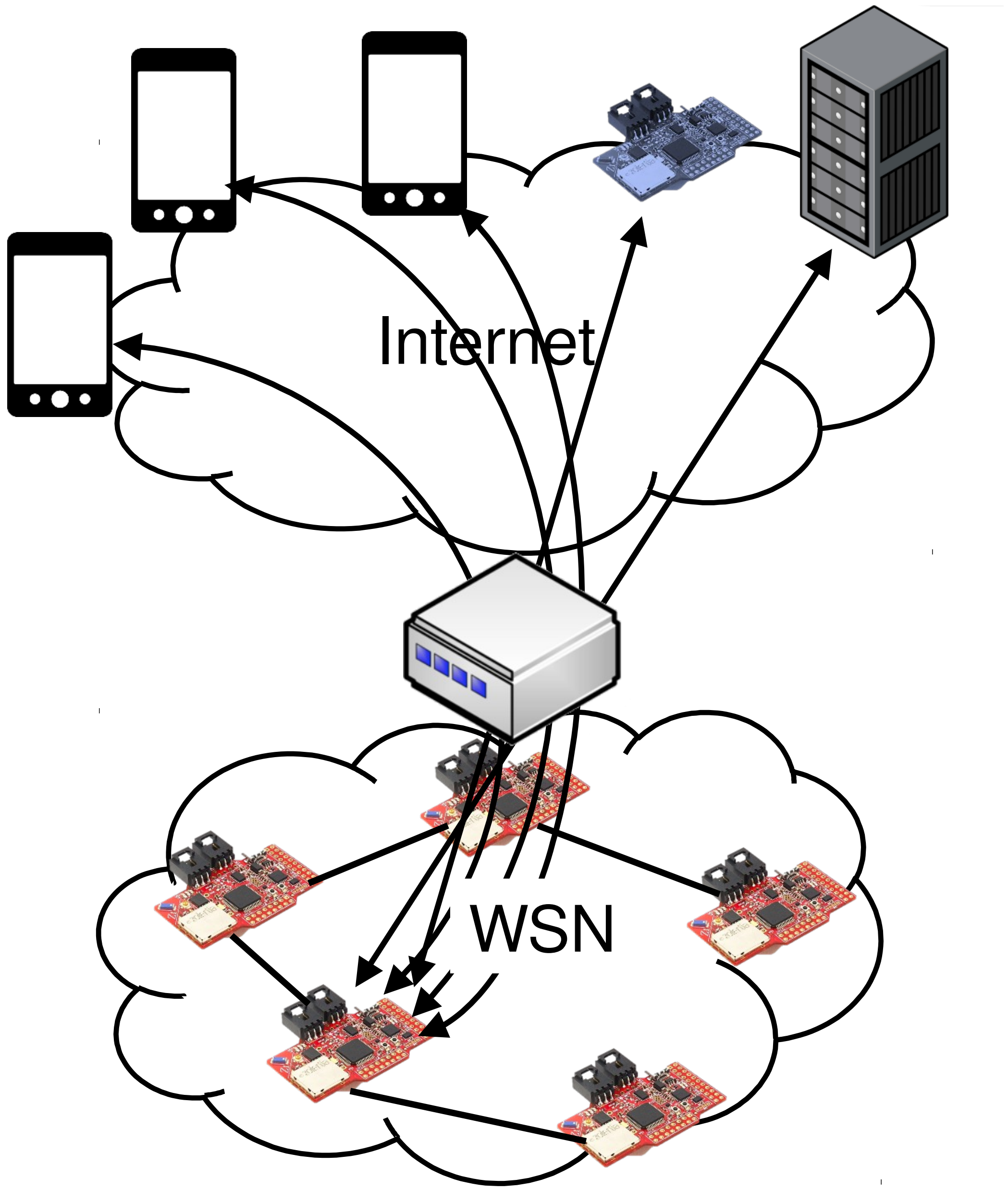
RESEARCH CHALLENGES IN CORE

Efficient Resource Utilization

Usability

Heterogeneity

CHALLENGE I: EFFICIENT RESOURCE UTILIZATION



Resource efficient access control in an open WoT?

- Authentication? Public keys, certificates?
- Security handshake: verbose?
- Access control rules based on time, location, identity, resource?
- Expend limited resources on unauthorized requests?

RESEARCH CHALLENGES IN CORE

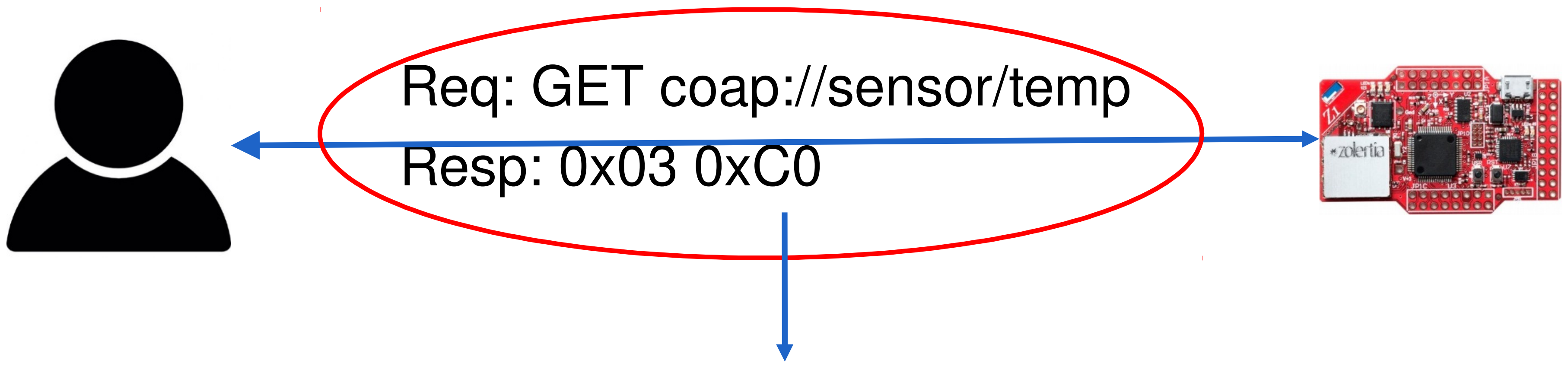
Efficient Resource Utilization

Usability

Heterogeneity

CHALLENGE II: USABILITY

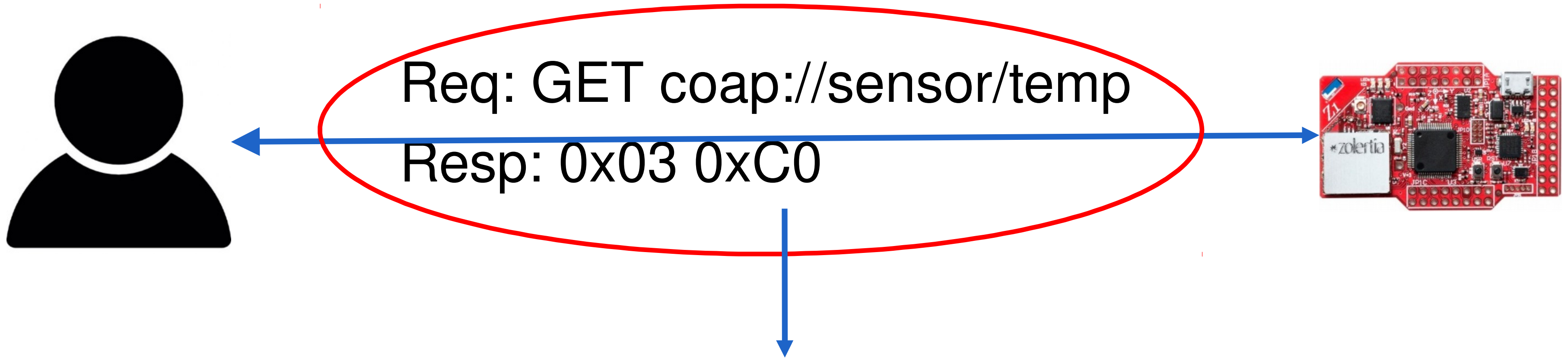
User interactions with constrained WoT devices?



Binary response without any visualization.
How should data be rendered? What about actuators?

CHALLENGE II: USABILITY

User interactions with constrained WoT devices?



Binary response without any visualization.
How should data be rendered? What about actuators?

Limitations of constrained devices prohibit hosting a UI:

- Simple index page based on the popular bootstrap template:
  44.6KB JS, 38.4 KB CSS and 6.5 KB HTML = **89.6KB of data**
- C1 devices have ~**100KB ROM** to fit the operating system and application
- Impact of additional communication.

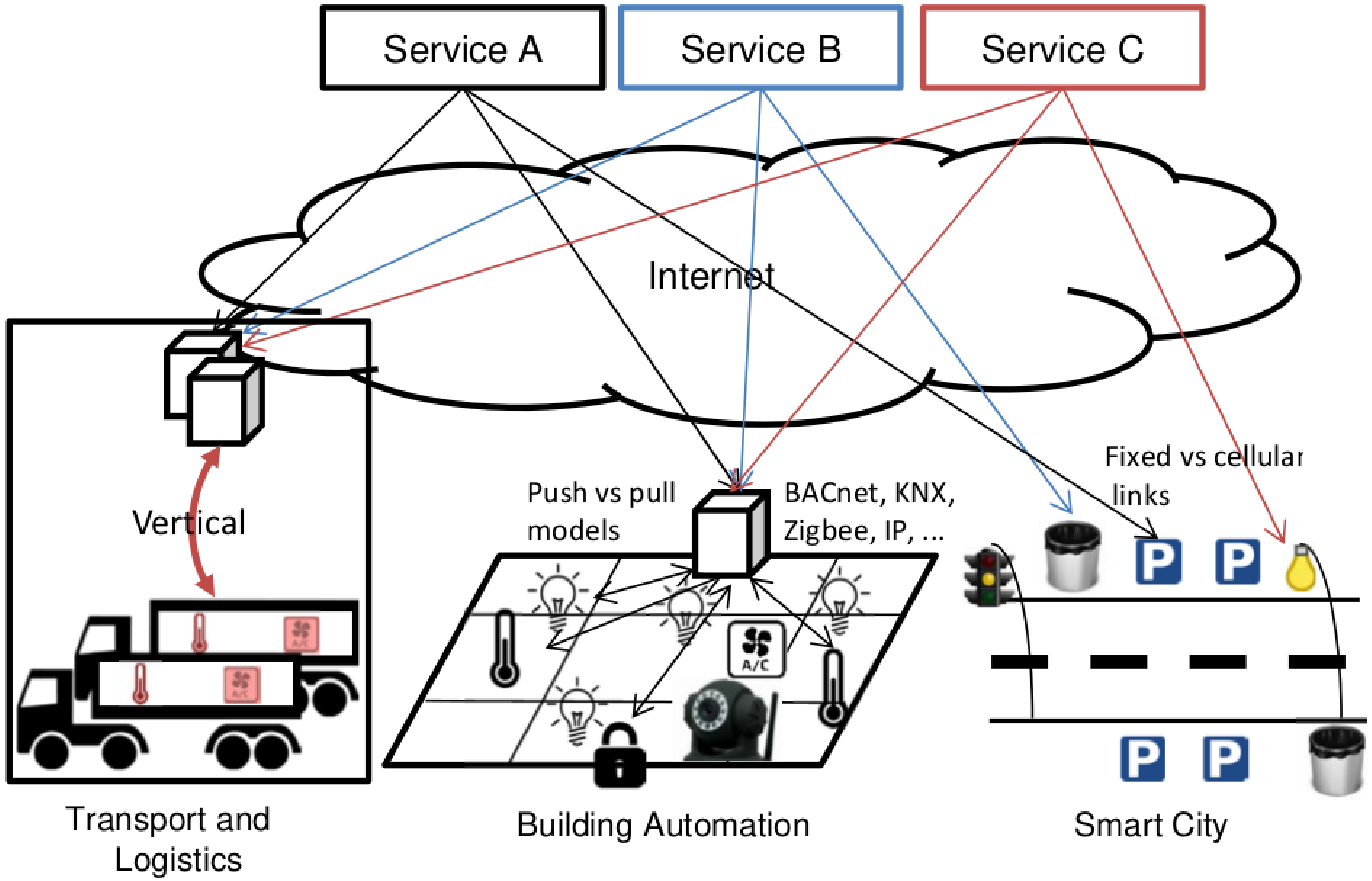
RESEARCH CHALLENGES IN CORE

Efficient Resource Utilization

Usability

Heterogeneity

CHALLENGE III: HETEROGENEITY



Cross-domain service providers have to interface with domain-specific:

- Connectivity options
- Standards and protocols
- Application models
- Data formats

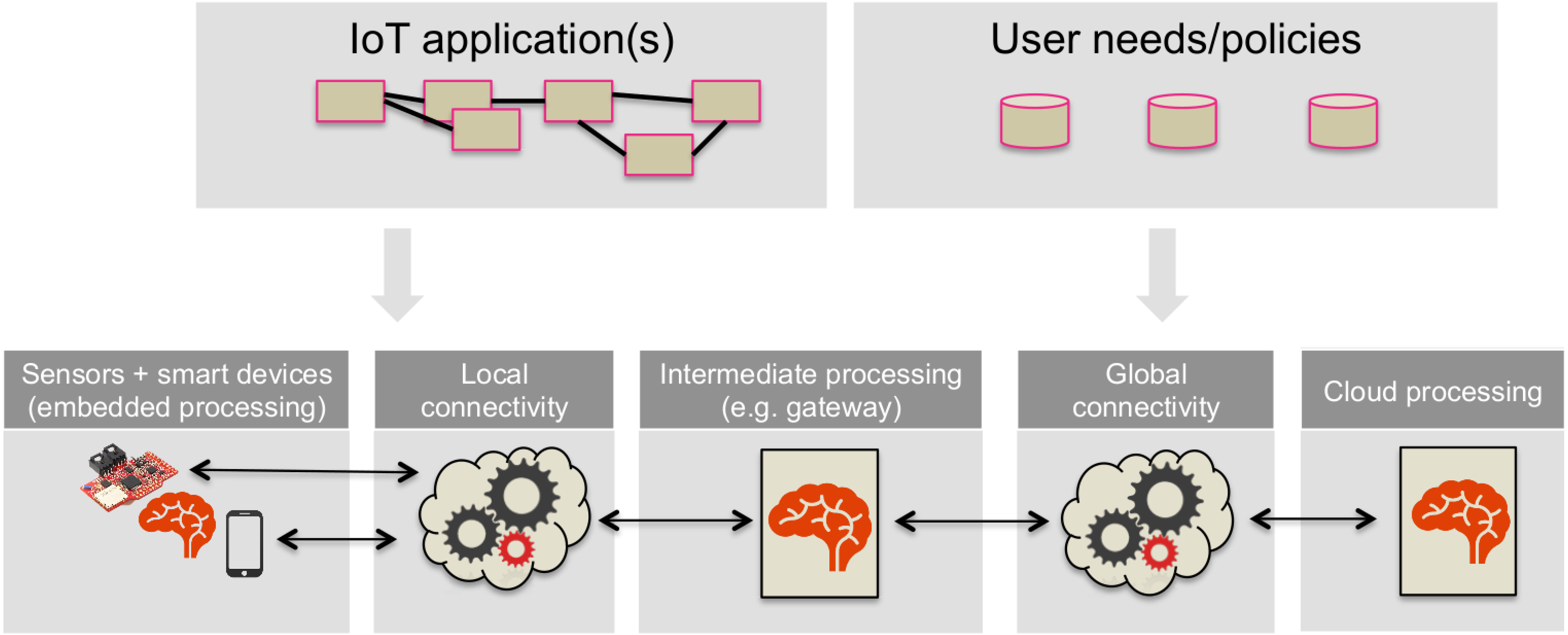
RESEARCH GOALS

- New technologies for the constrained Web of Things BUT challenges remain:
  - **Efficient resource utilization**: open standards should not threaten the operation of CoRE: e.g. battery lifetime.
  - **Usability**: how to support user interactions in CoRE?
  - **Heterogeneity**: different application models, proprietary protocols
- **Goal?**

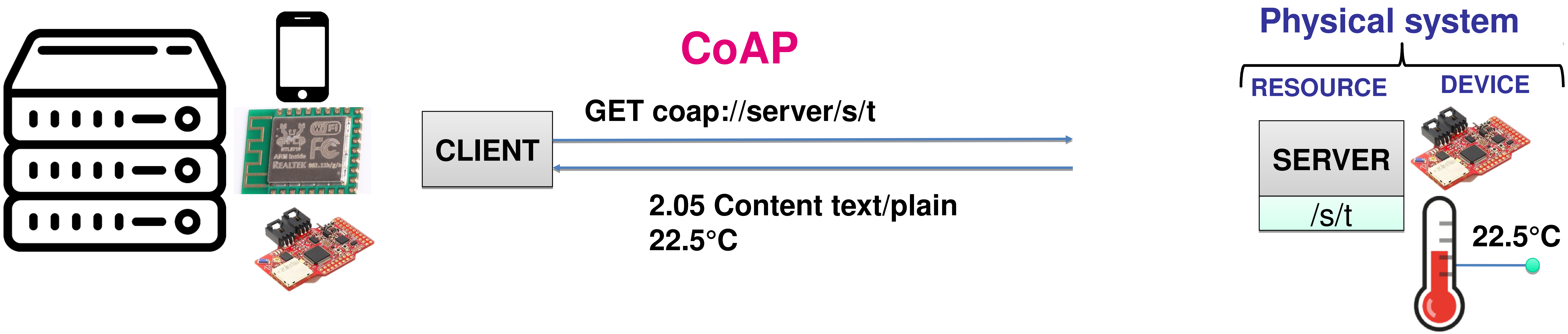
  Remove technical barriers for adopting open web standards in the constrained WoT in order to accelerate adoption and maximize interoperability
- **How?**

  <u>Distributed Intelligence</u> and <u>Sensor Function Virtualization</u> enable resourceful systems to extend constrained devices and solve these challenges.

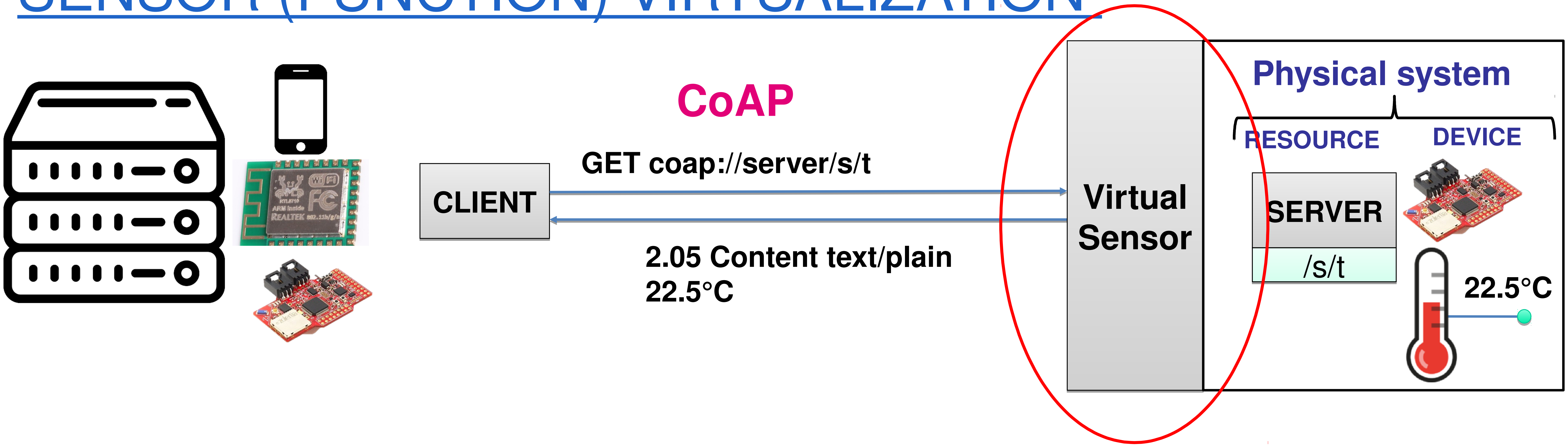
THE DISTRIBUTED INTELLIGENCE CONCEPT



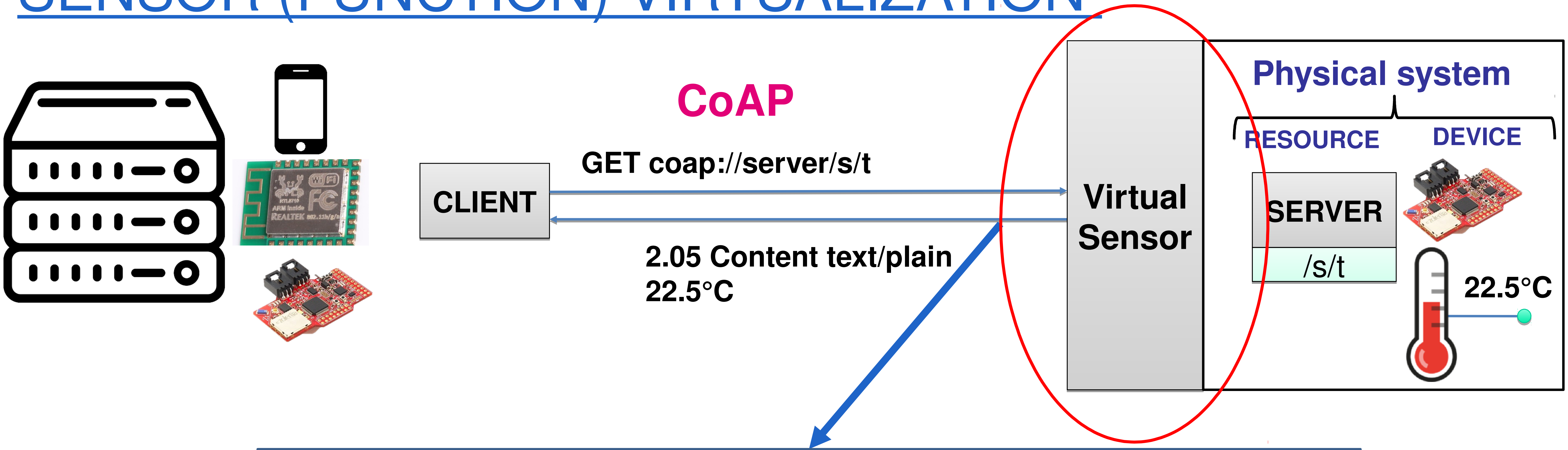
SENSOR (FUNCTION) VIRTUALIZATION



SENSOR (FUNCTION) VIRTUALIZATION



SENSOR (FUNCTION) VIRTUALIZATION



Hosted on resourceful systems: gateways, fog or cloud

Offload functionality: e.g. access control

Implement new features: e.g. virtual resources, caching

3. RESULTS:

EFFICIENT RESOURCE UTILIZATION

USABILITY

HETEROGENEITY

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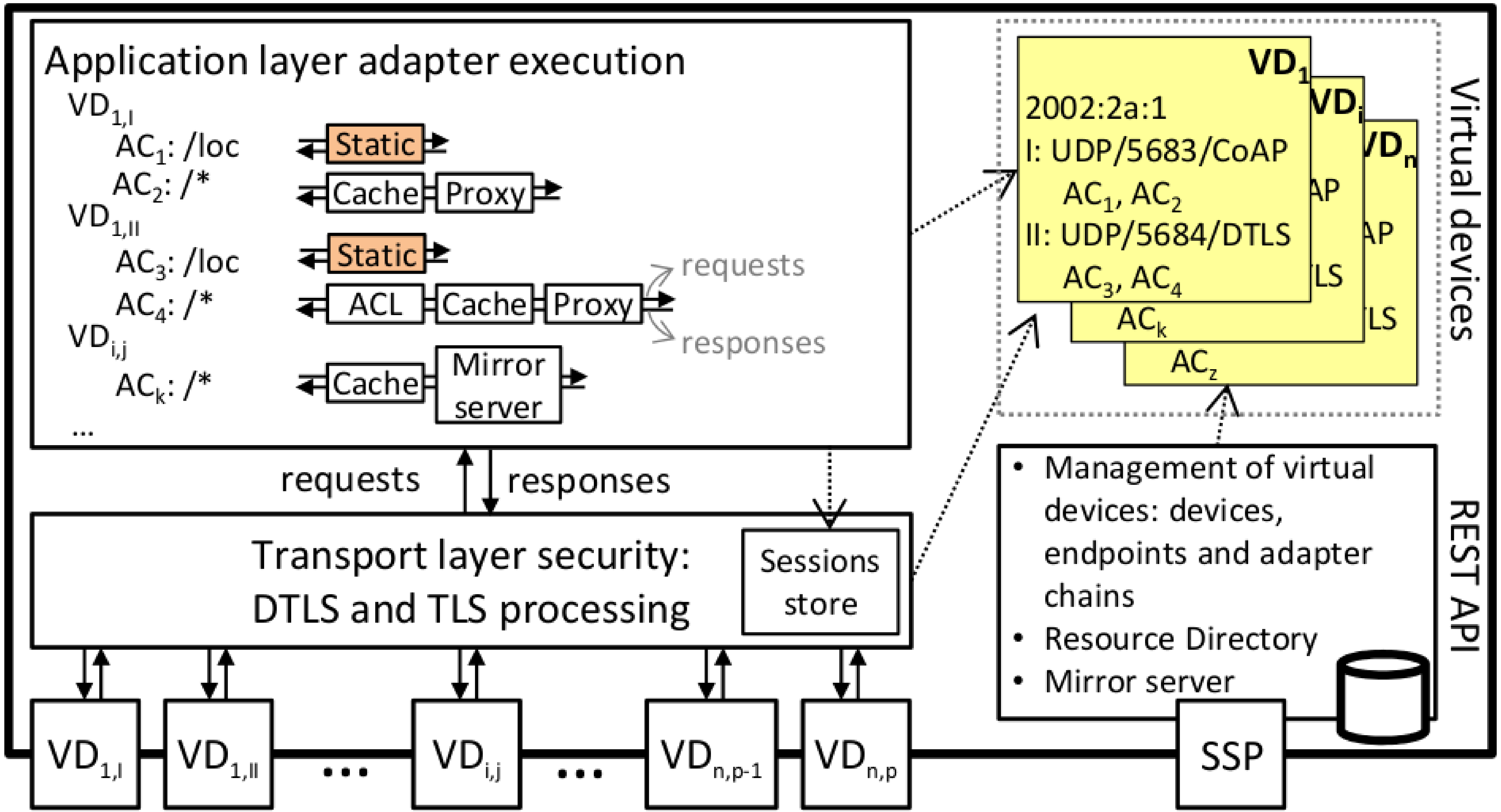
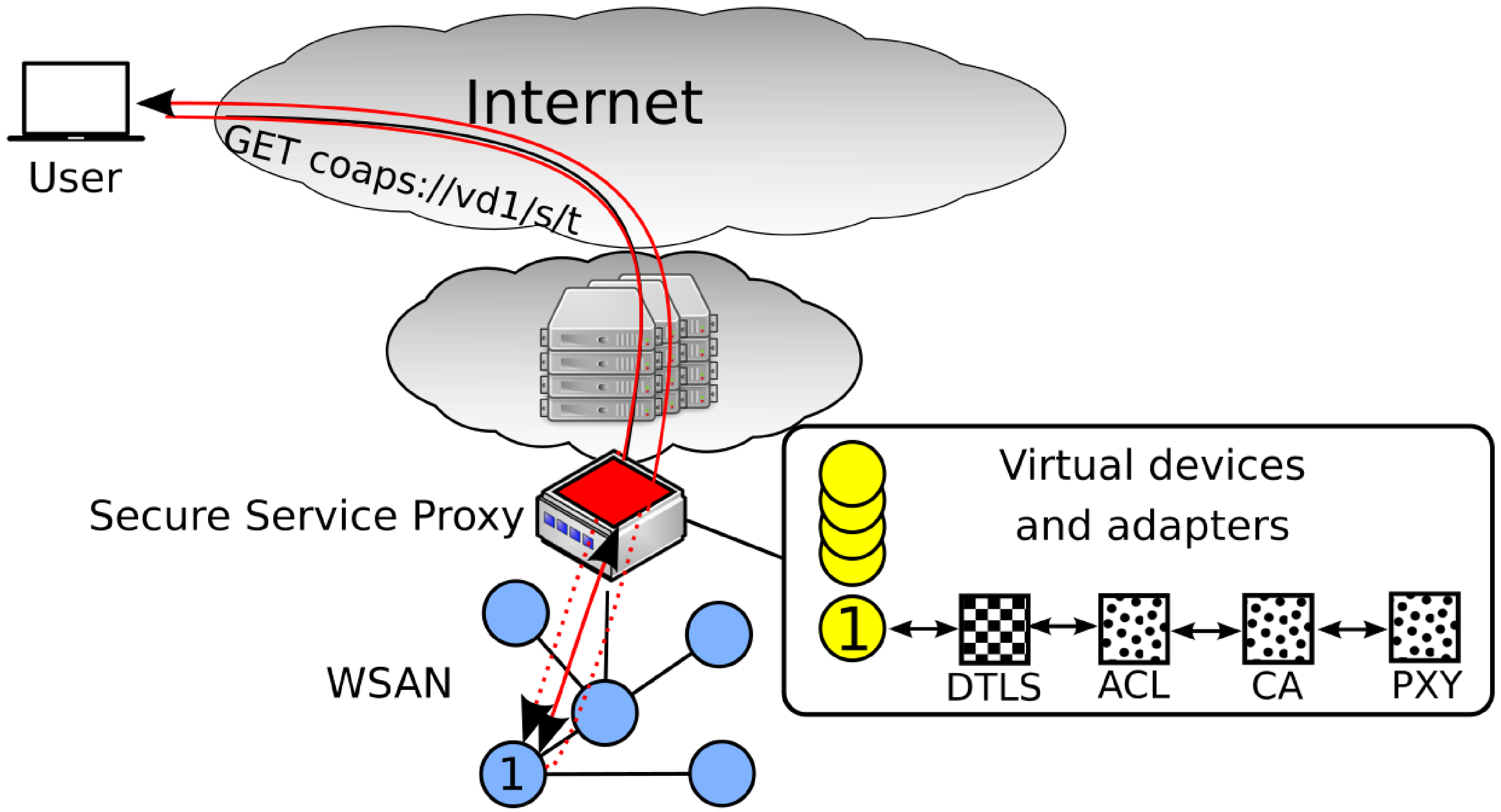
SECURE SERVICE PROXY: DESIGN



RESOURCE EFFICIENT ACCESS CONTROL



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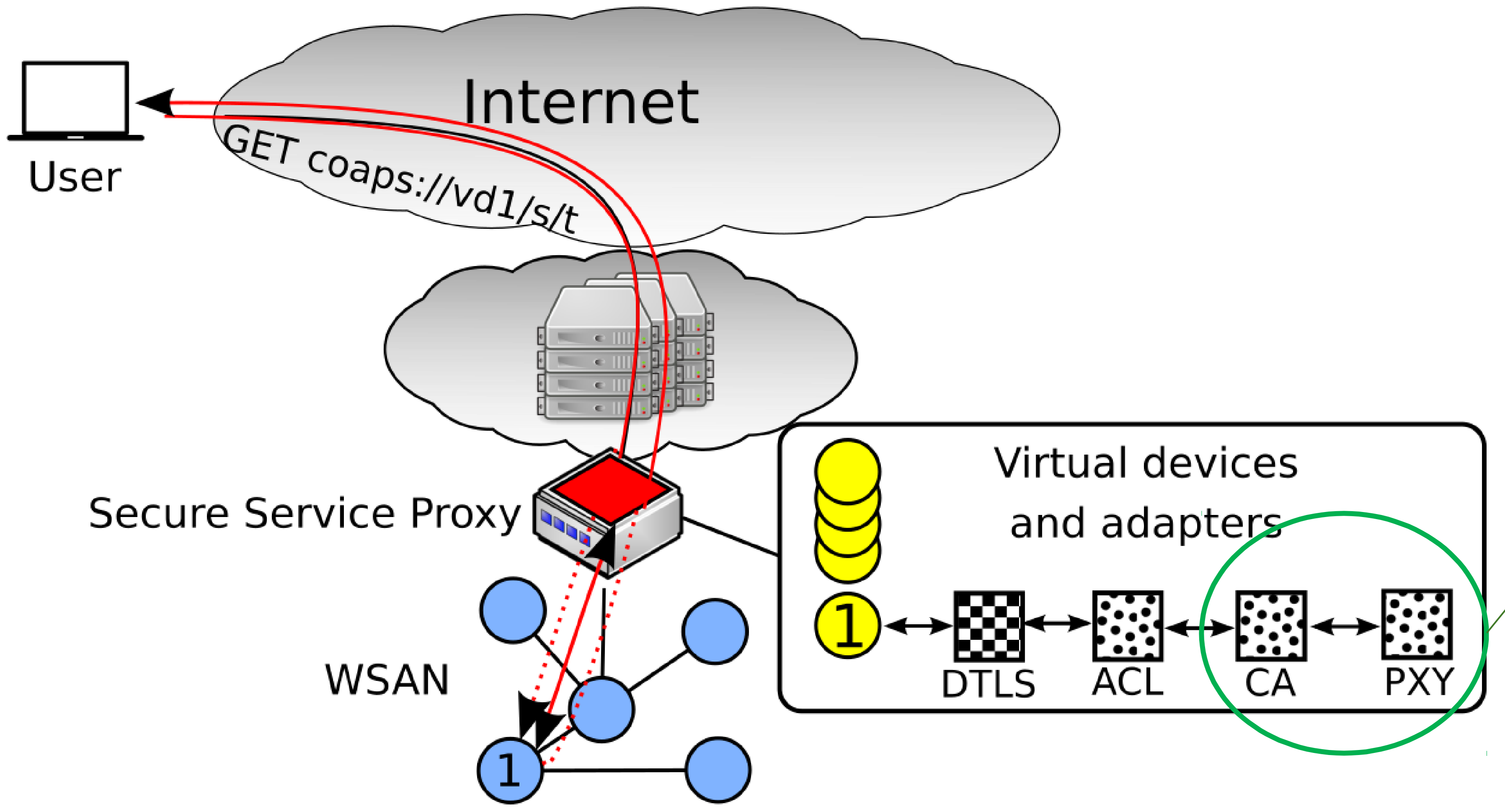
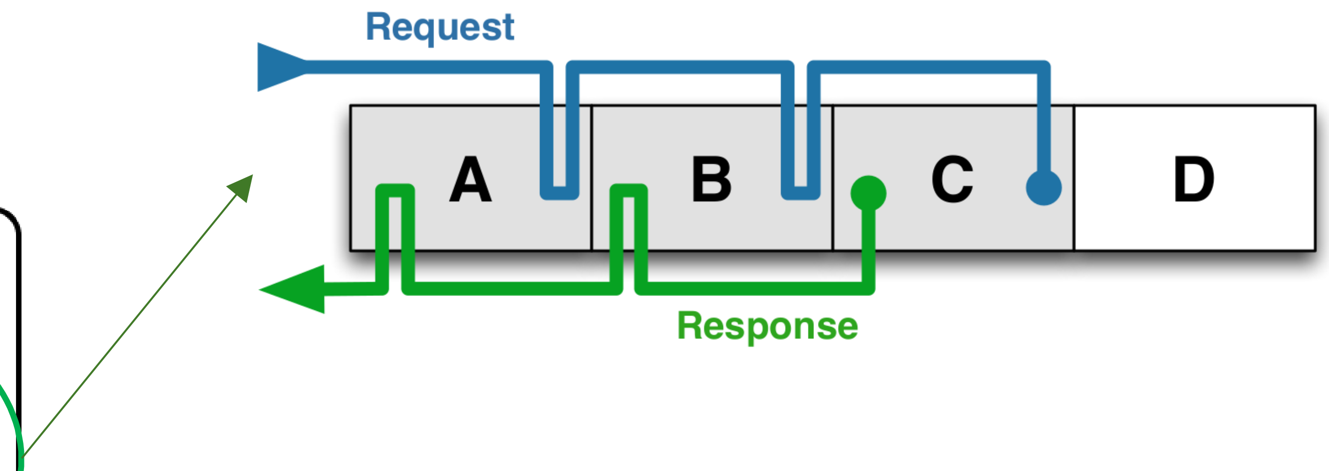
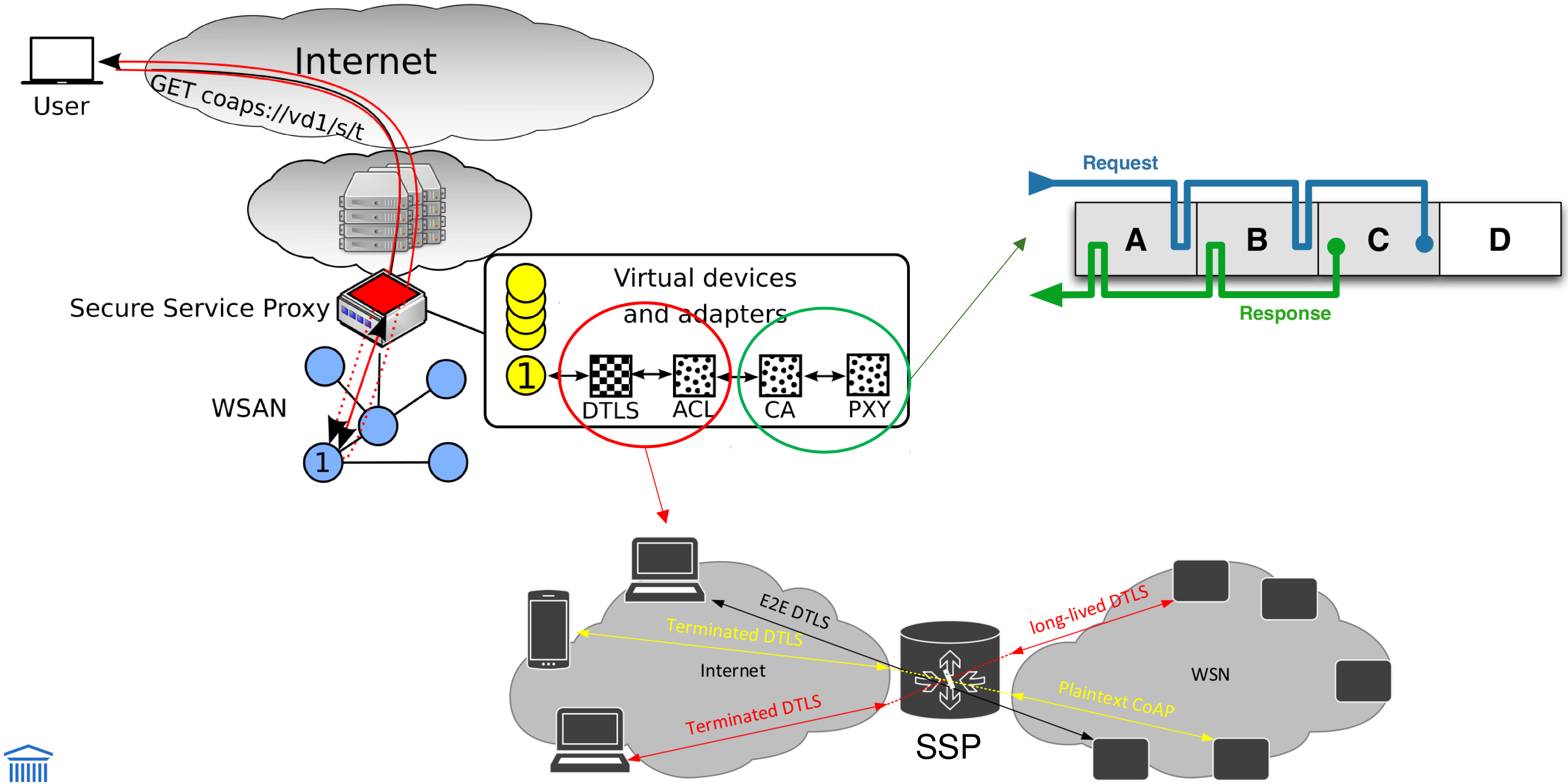
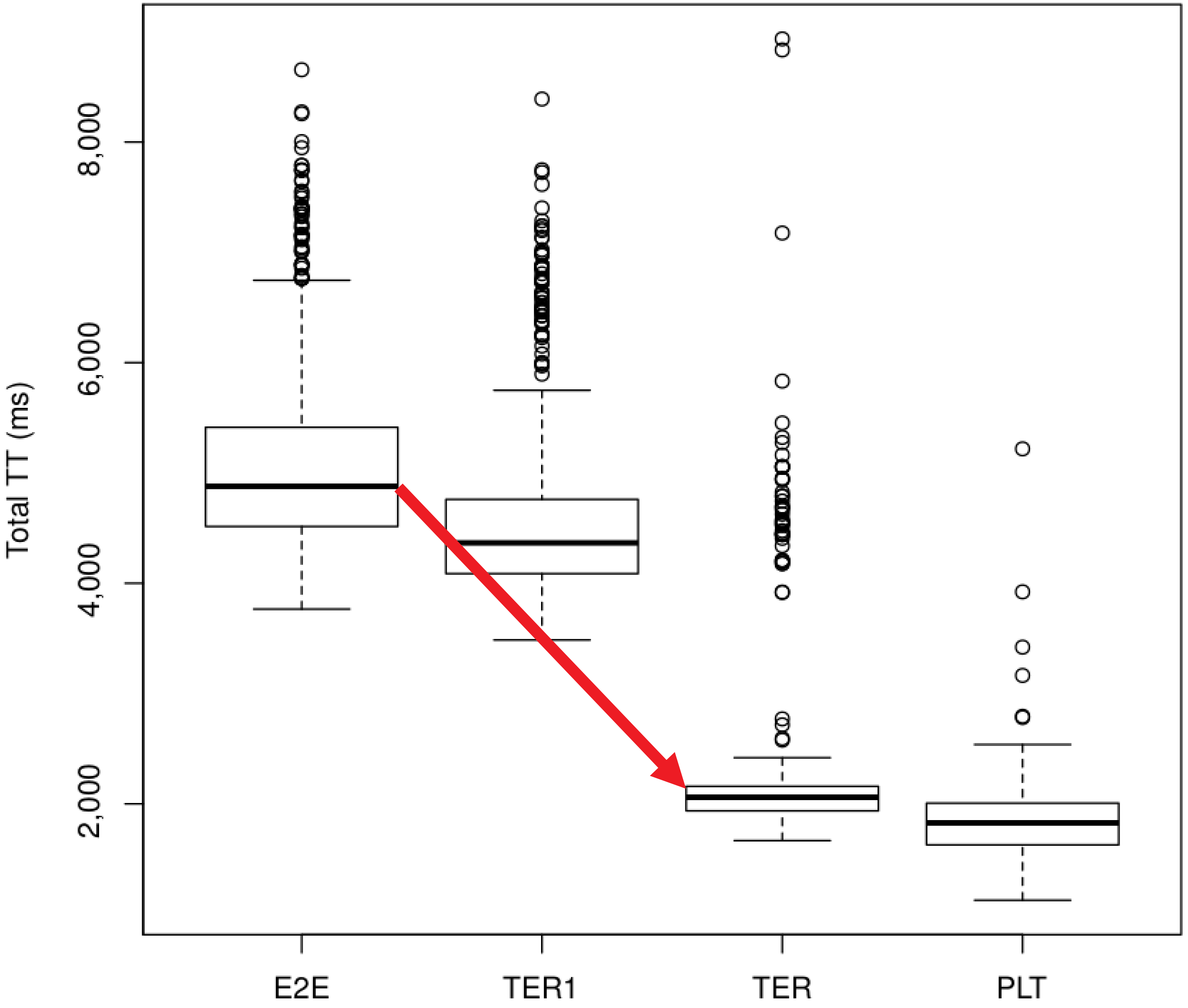




RESOURCE EFFICIENT ACCESS CONTROL



LONG-LIVED DTLS SESSIONS REDUCE DELAY



Long-lived DTLS sessions cut the total transaction time (TTT) in half: median ~5000ms → 2000ms

Comparable TTTs to plain-text reference case

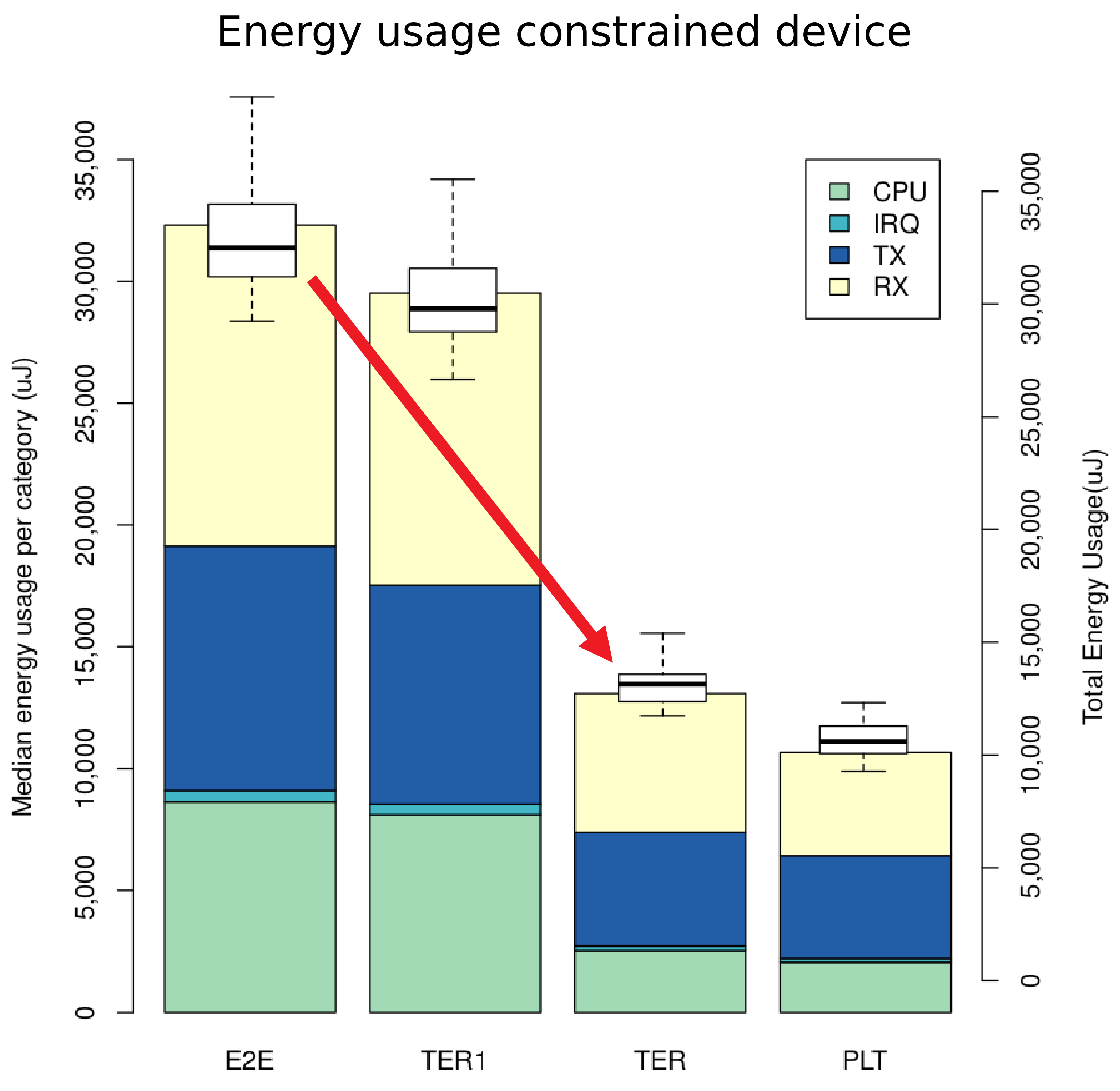
CoRE transaction:

- Setup DTLS session (handshake)
- Discover (GET .well-known/core)
- Read (GET /s)
- Write (PUT /a)
- Close DTLS session (Finished)

LONG-LIVED DTLS SESSIONS SAVE ENERGY

Factor two reduction in median energy consumption.

Biggest energy savings stem from reduction in radio time.



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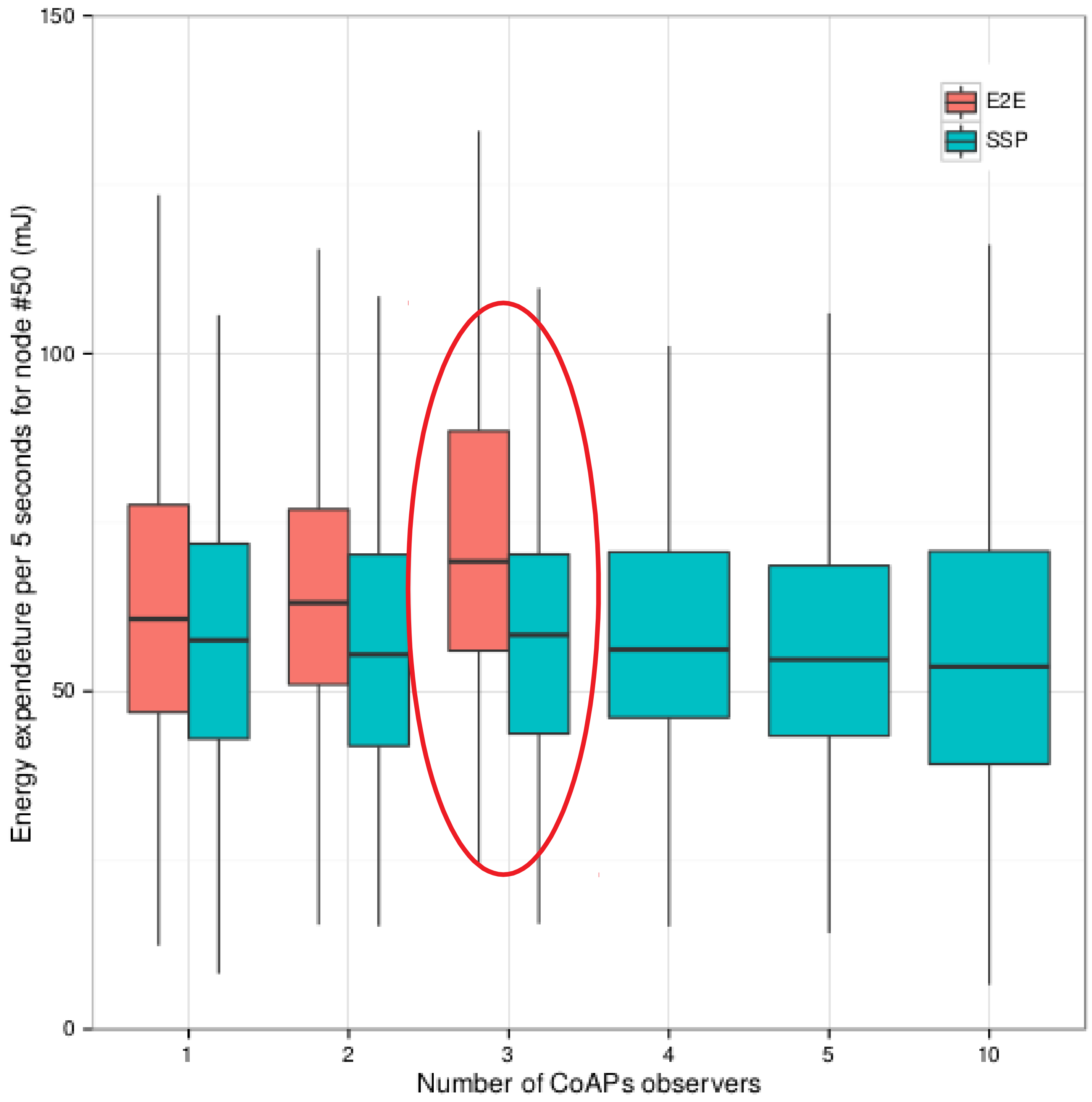
COMBINING OBSERVE SESSIONS SAVES ENERGY

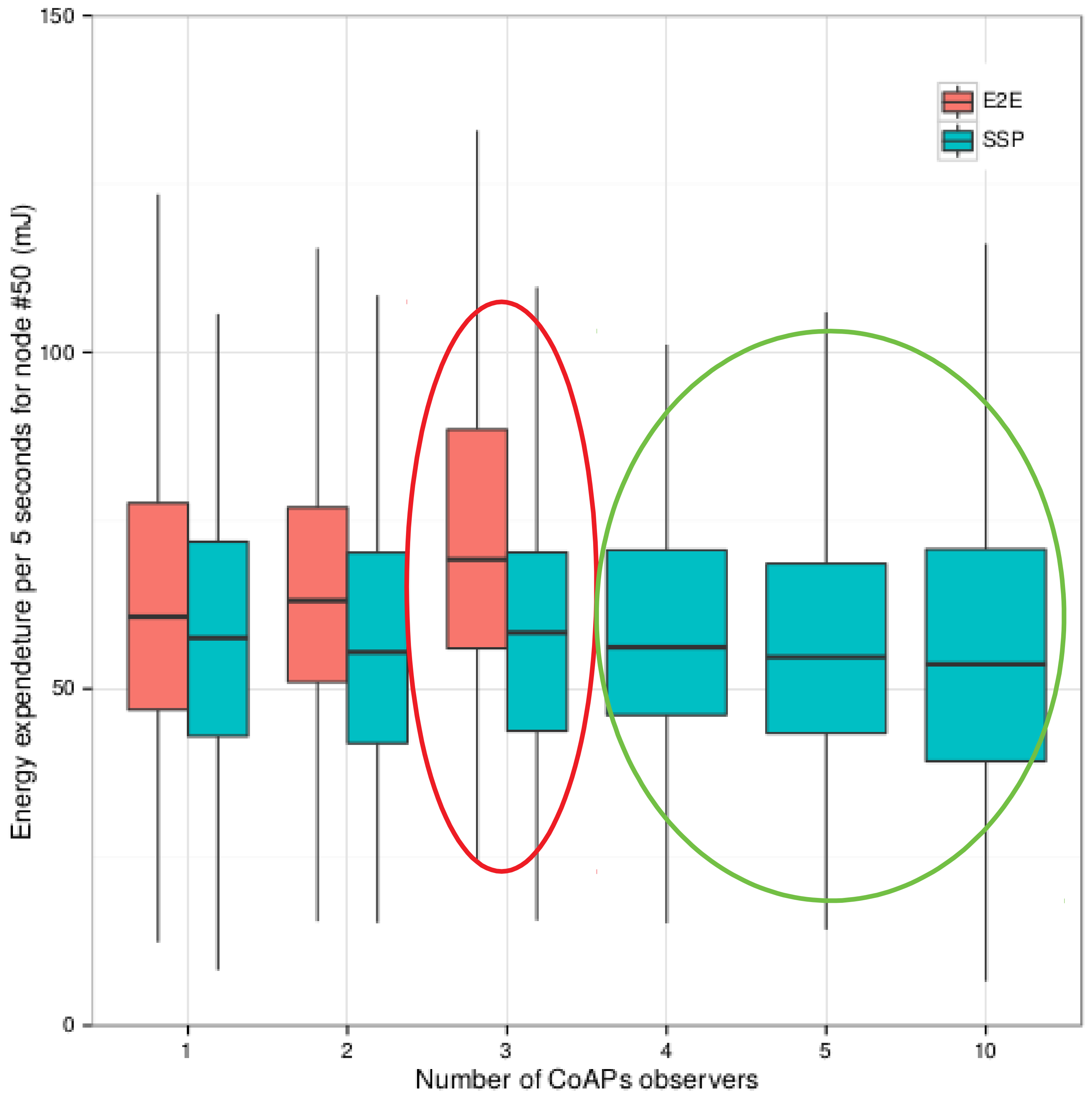


(a) One second notification interval.

Combine multiple CoAP observe sessions at the SSP

10% reduction in median energy consumption

COMBINING OBSERVE SESSIONS SAVES ENERGY



(a) One second notification interval.

Combine multiple CoAP observe sessions at the SSP

10% reduction in median energy consumption

More than three simultaneous sessions.

3. RESULTS:

EFFICIENT RESOURCE UTILIZATION

USABILITY

HETEROGENEITY

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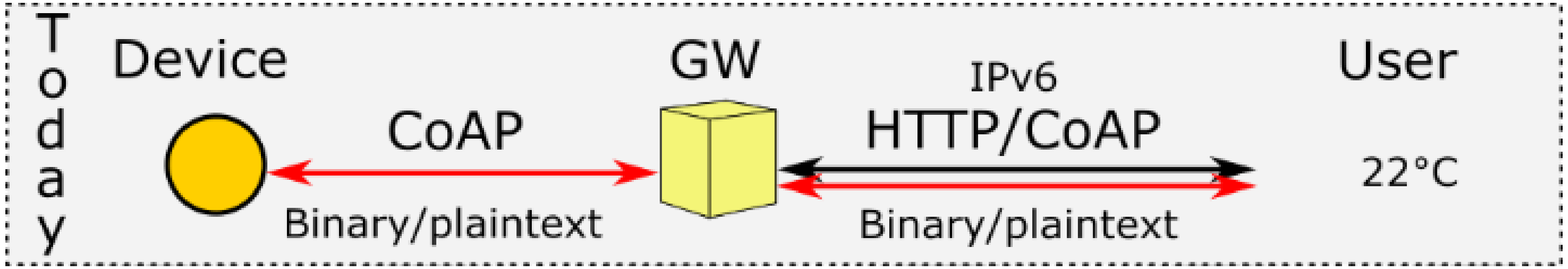
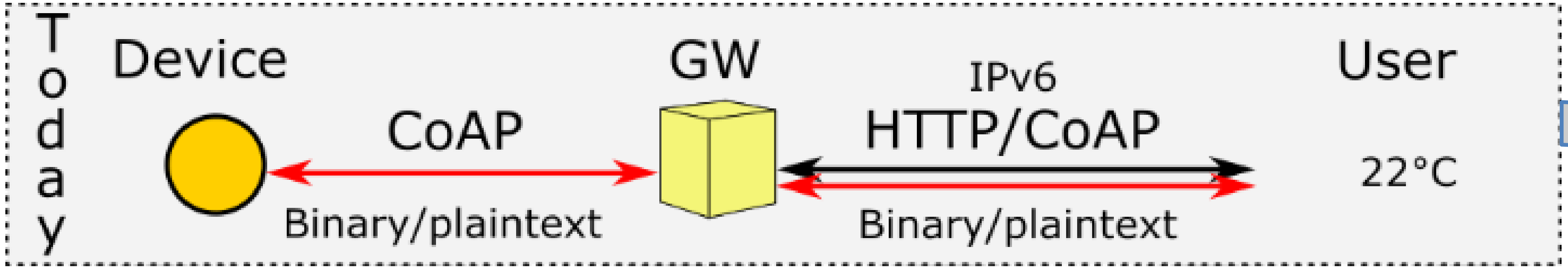
TEMPLATE-BASED UI RENDERING



E2E UDP/CoAP or TCP/HTTP via GW

Unaltered CoAP responses (e.g. binary encoding)

TEMPLATE-BASED UI RENDERING



E2E UDP/CoAP or TCP/HTTP via GW

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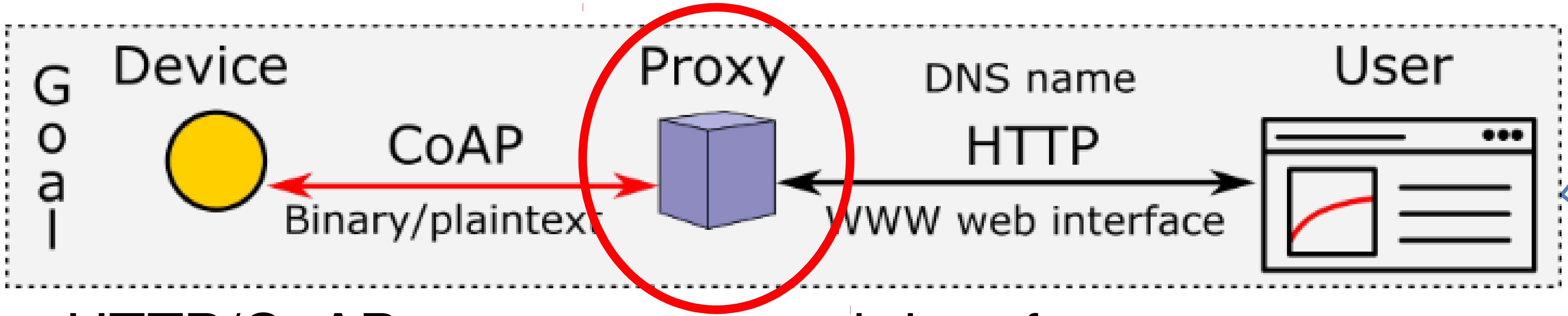

<u>HTTP/CoAP proxy</u> serves web interfaces to users

Proxy and web interface translate CoAP responses

Proxy contains a database of web templates

Standard web technology:

→ Web browser compatible

→ Cross-platform support

→ Rich UI's :e.g. responsive design

WEB UI FOR RESOURCE DISCOVERY

z1rc2055.test/.well-known/core

Easy to use IoT

z1rc2055.test/.well-known/core

Web link	Title	Resource type	Content type	HTTP link
/.well-known/core			40	http://z1rc2055.test/.well-known/core
/deviceName		ibcn.dev.name		http://z1rc2055.test/deviceName
/owner		ibcn.owner		http://z1rc2055.test/owner
/d		ibcn.dev		http://z1rc2055.test/d
/sensors/temp		ibcn.temp		http://z1rc2055.test/sensors/temp
/actuators/fan		ibcn.fan		http://z1rc2055.test/actuators/fan
/location		ibcn.location	0	http://z1rc2055.test/location
/image		ibcn.image	1001	http://z1rc2055.test/image
/dns		ibcn.dns	0	http://z1rc2055.test/dns

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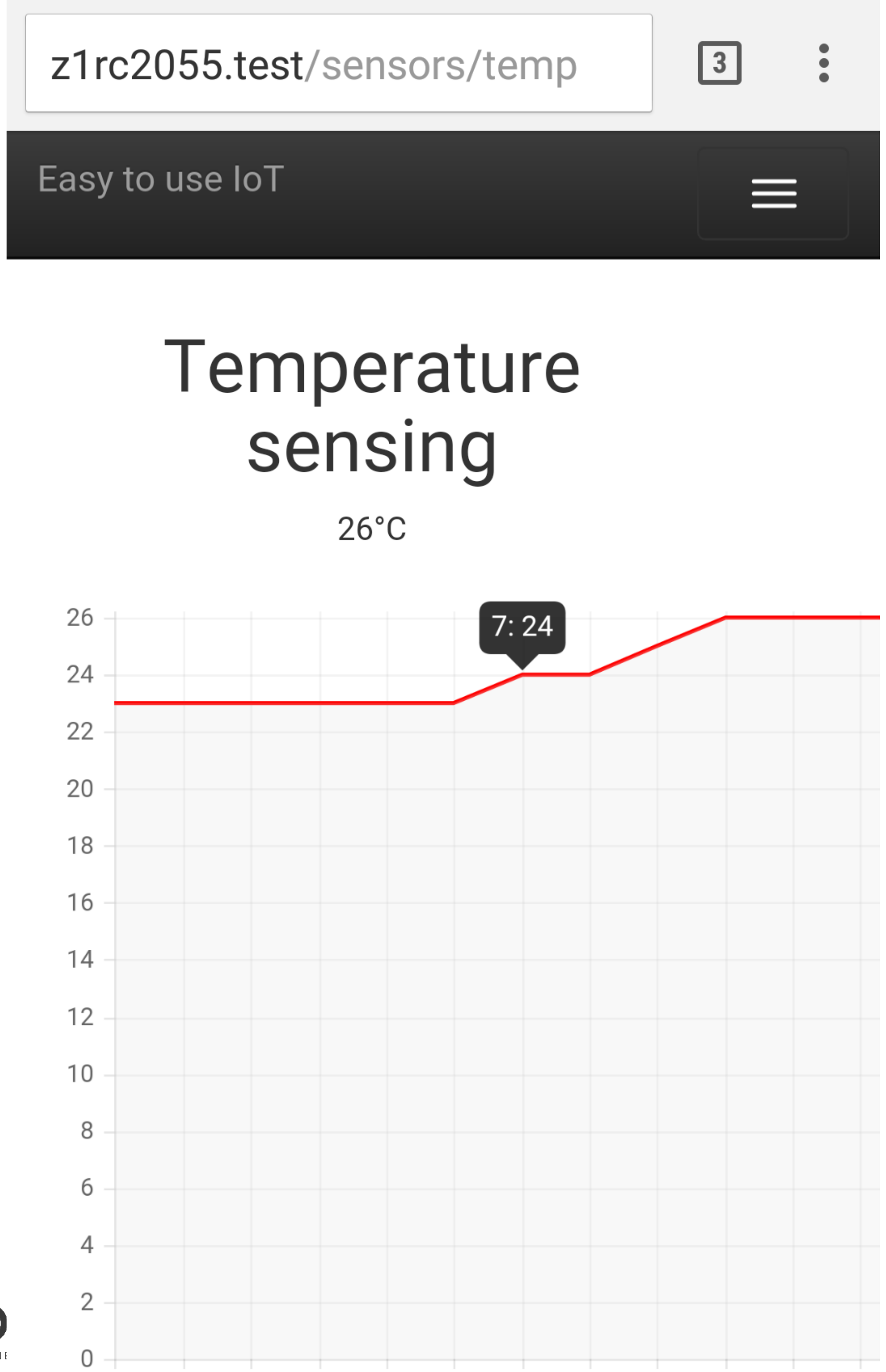
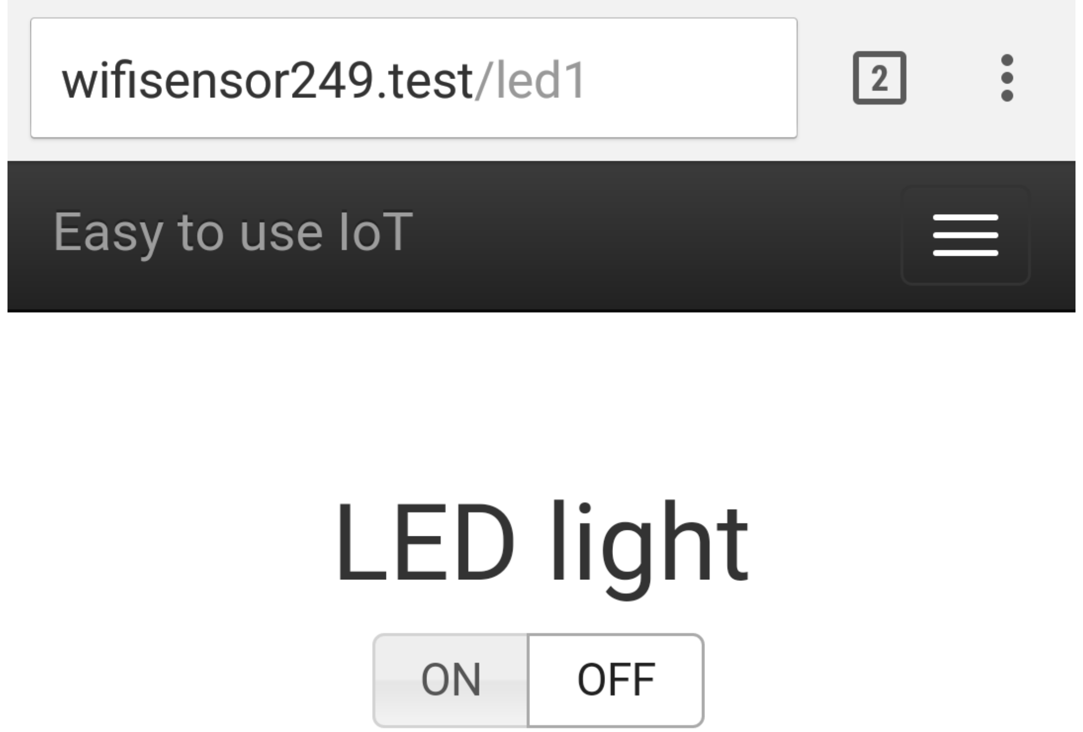
WEB UI FOR SENSING AND ACTUATING





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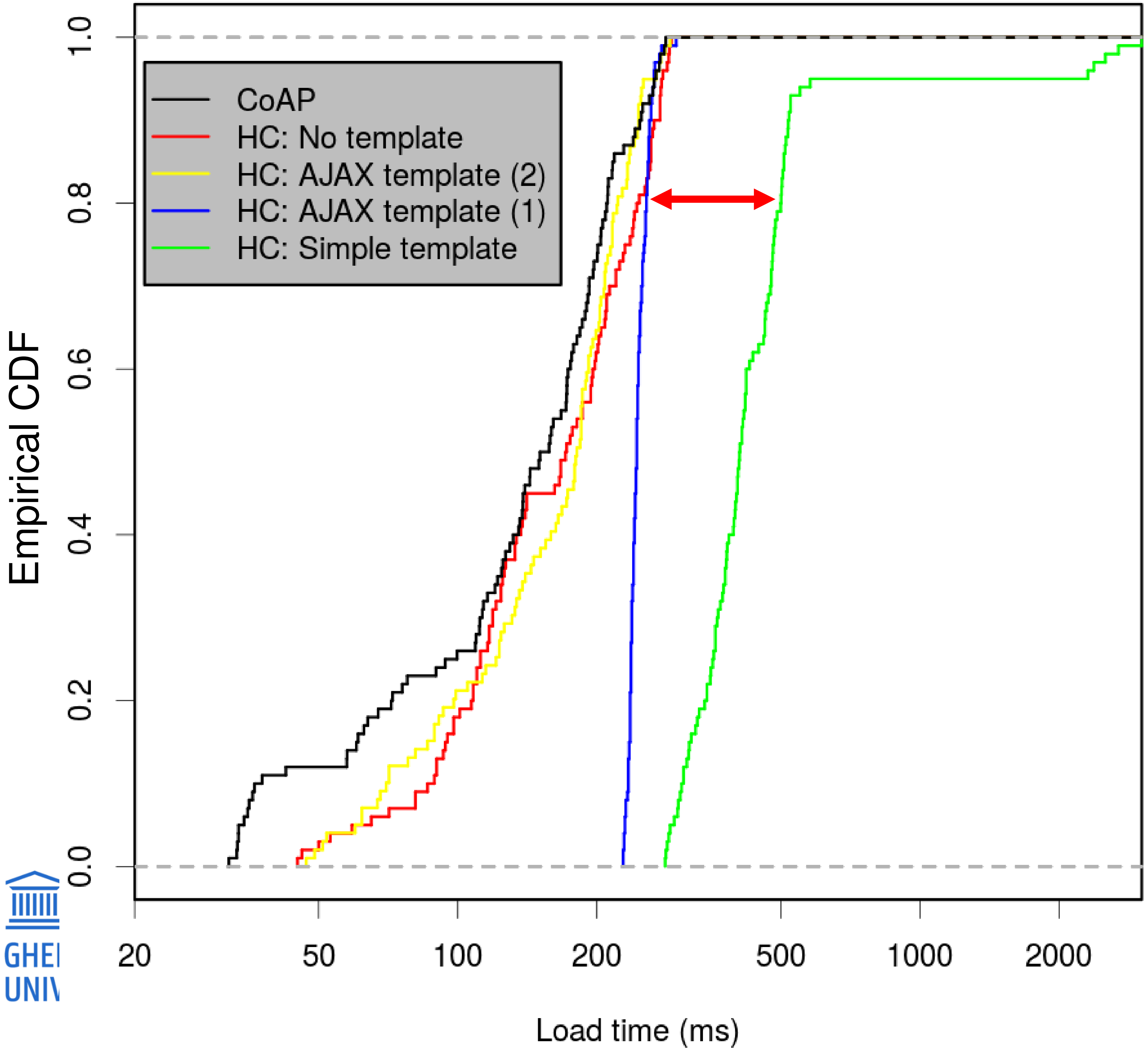
UI LOAD TIMES



Non-blocking template (AJAX) load time is independent of CoAP response time

Guarantees UI responsiveness regardless of round trip time to constrained device

3. RESULTS:

EFFICIENT RESOURCE UTILIZATION

USABILITY

HETEROGENEITY

CLOUD PLATFORM FOR INTEGRATING HETEROGENEOUS DEVICES

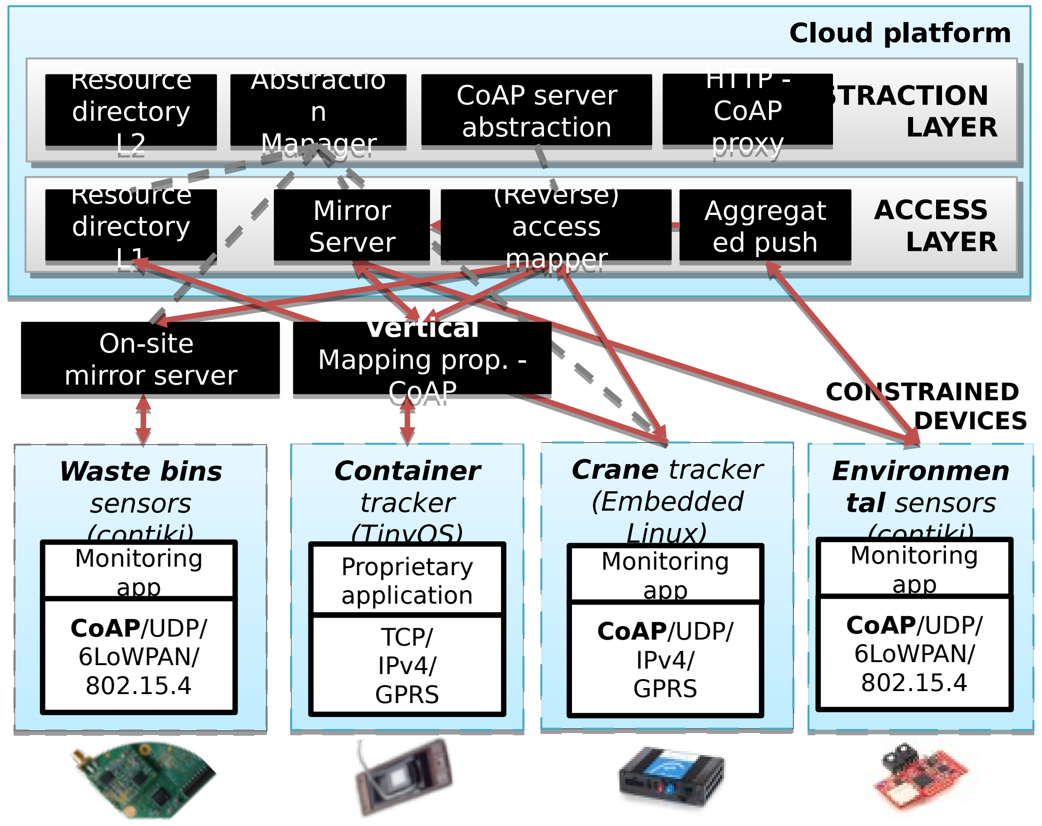
CONSTRAINED DEVICES

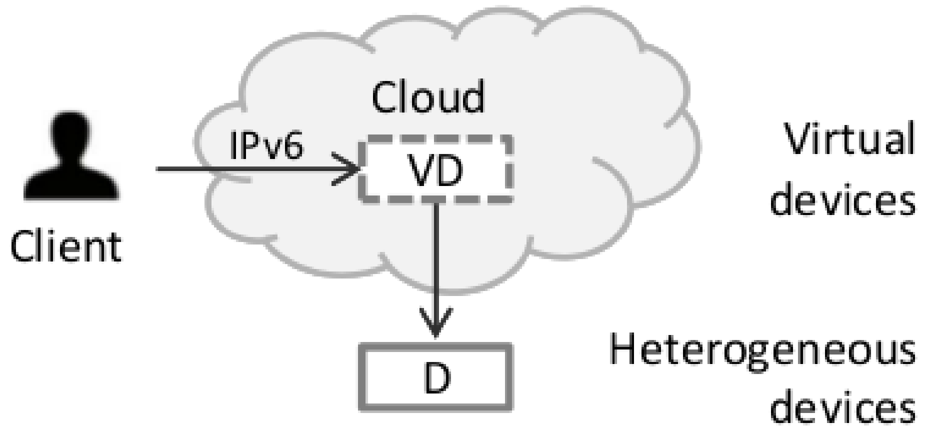
***Waste bins** sensors (contiki)*	***Container** tracker (TinyOS)*	***Crane** tracker (Embedded Linux)*	***Environmental** sensors (contiki)*
Monitoring app	Proprietary application	Monitoring app	Monitoring app
CoAP/UDP/ 6LoWPAN/ 802.15.4	TCP/ IPv4/ GPRS	**CoAP**/UDP/ IPv4/ GPRS	**CoAP**/UDP/ 6LoWPAN/ 802.15.4

Heterogeneity considered:

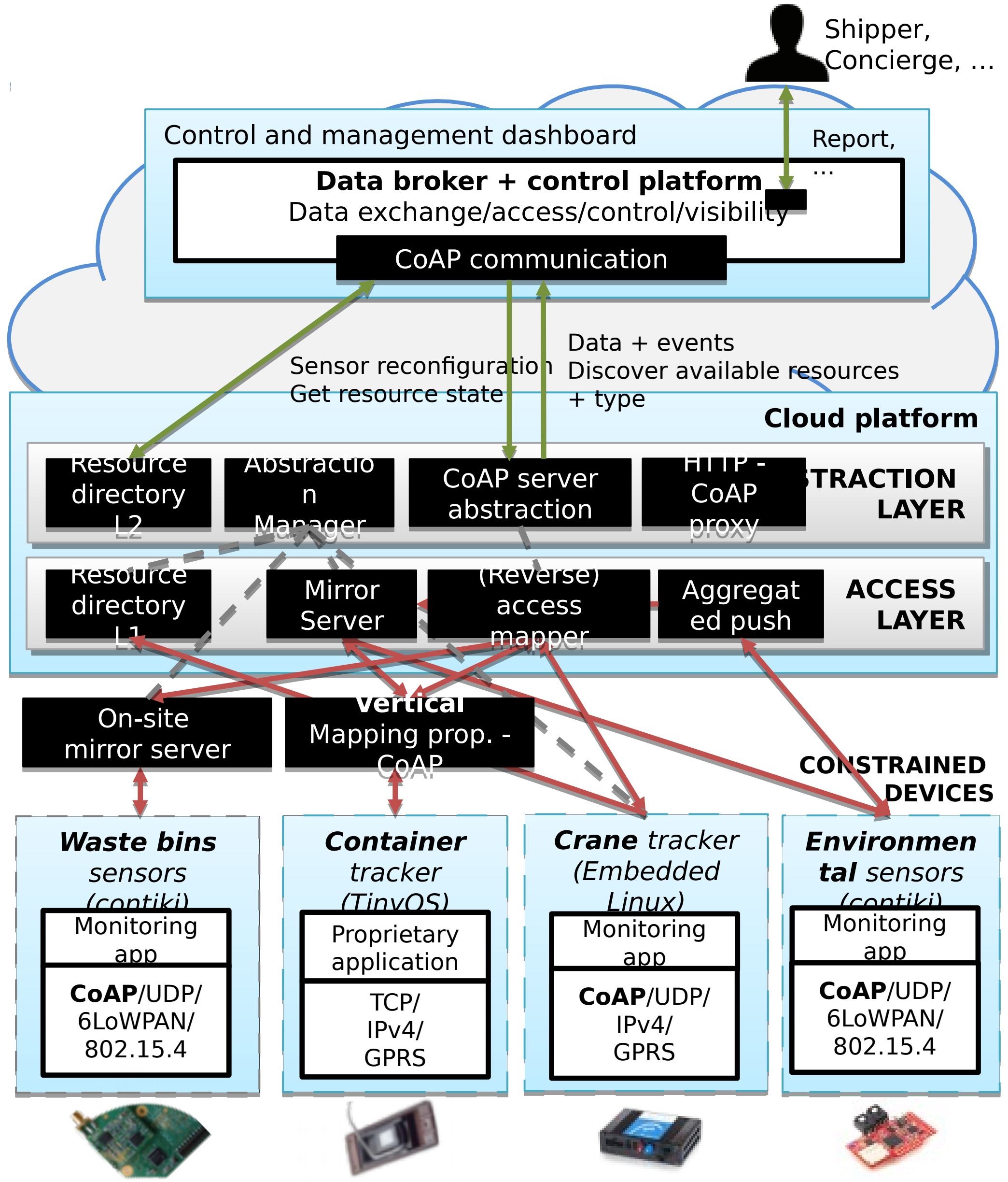
- Different devices/OS: embedded linux, bare metal, contiki & tinyos
- Proprietary vs standards-based communication
- PUSH vs PULL communication model
- Sleepy vs (near) always-on devices

CLOUD PLATFORM FOR INTEGRATING HETEROGENEOUS DEVICES





CLOUD PLATFORM FOR INTEGRATING HETEROGENEOUS DEVICES



DeviceManagers | Sensor Data | OneAccess

IP-address: coap://[2001:6a8:1d80:600::3]:5683
Category: Trashcan
Description: Trashcan 1

Name	Type	Description	Data	Readable	Writable
/battery	Text	Created via rest	View data	N/a	N/a
/lastrssi	Text	Created via rest	View data	N/a	N/a
/s/o	offset	Created via rest	View data	Read resource	Write to resource
/s/t	txlev	Created via rest	View data	Read resource	Write to resource
/s/u	update	Created via rest	View data	Read resource	Write to resource
/s/w	/s/w	Created via rest	View data	Read resource	Write to resource
/switch	Text	Created via rest	View data	N/a	N/a

IP-address: coap://[2001:6a8:1d80:600::4]:5683
Category: Trashcan
Description: Trashcan 2

Name	Type	Description	Data
/battery	Text	Created via rest	View data
/lastrssi	Text	Created via rest	View data
/s/o	offset	Created via rest	View data
/s/t	txlev	Created via rest	View data
/s/u	update	Created via rest	View data
/s/w	/s/w	Created via rest	View data
/switch	Text	Created via rest	View data

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4. THE INTERNET OF …

4. THE INTERNET OF … COWS!

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MONITORING DAIRY CATTLE

Monitor:

- Temperature
- Activity:
  - Position
  - Movement
  - Eating/drinking duration

\+ Cow calendar

MONITORING DAIRY CATTLE

Monitor:

- Temperature
- Activity:
  - Position
  - Movement
  - Eating/drinking duration

+ Cow calendar

Detect?

- Heat
- Illness
- Lameness
- Calving moment

How's my cow?
Where's my cow?
What is my cow doing?

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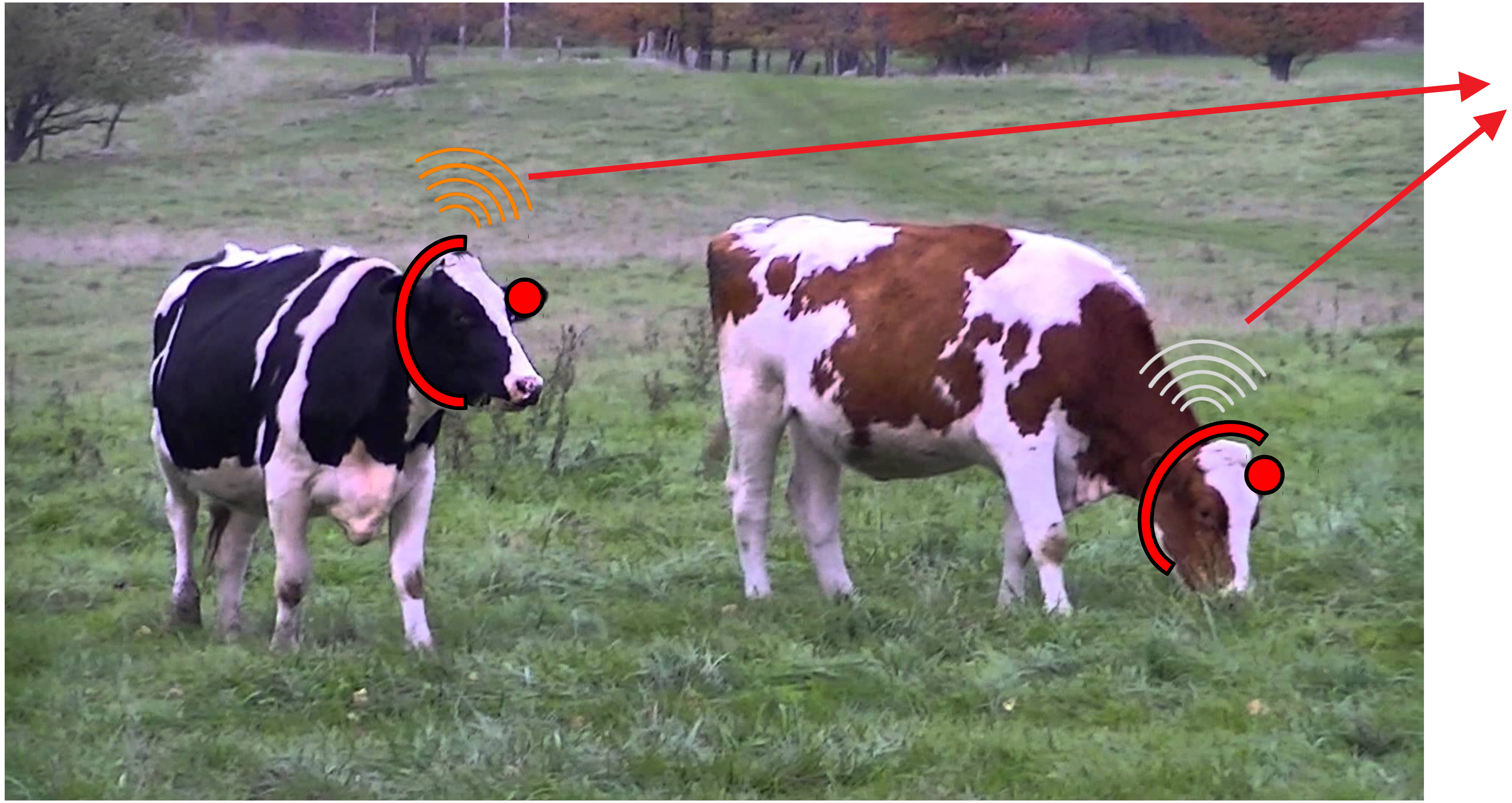
MONITORING DAIRY CATTLE



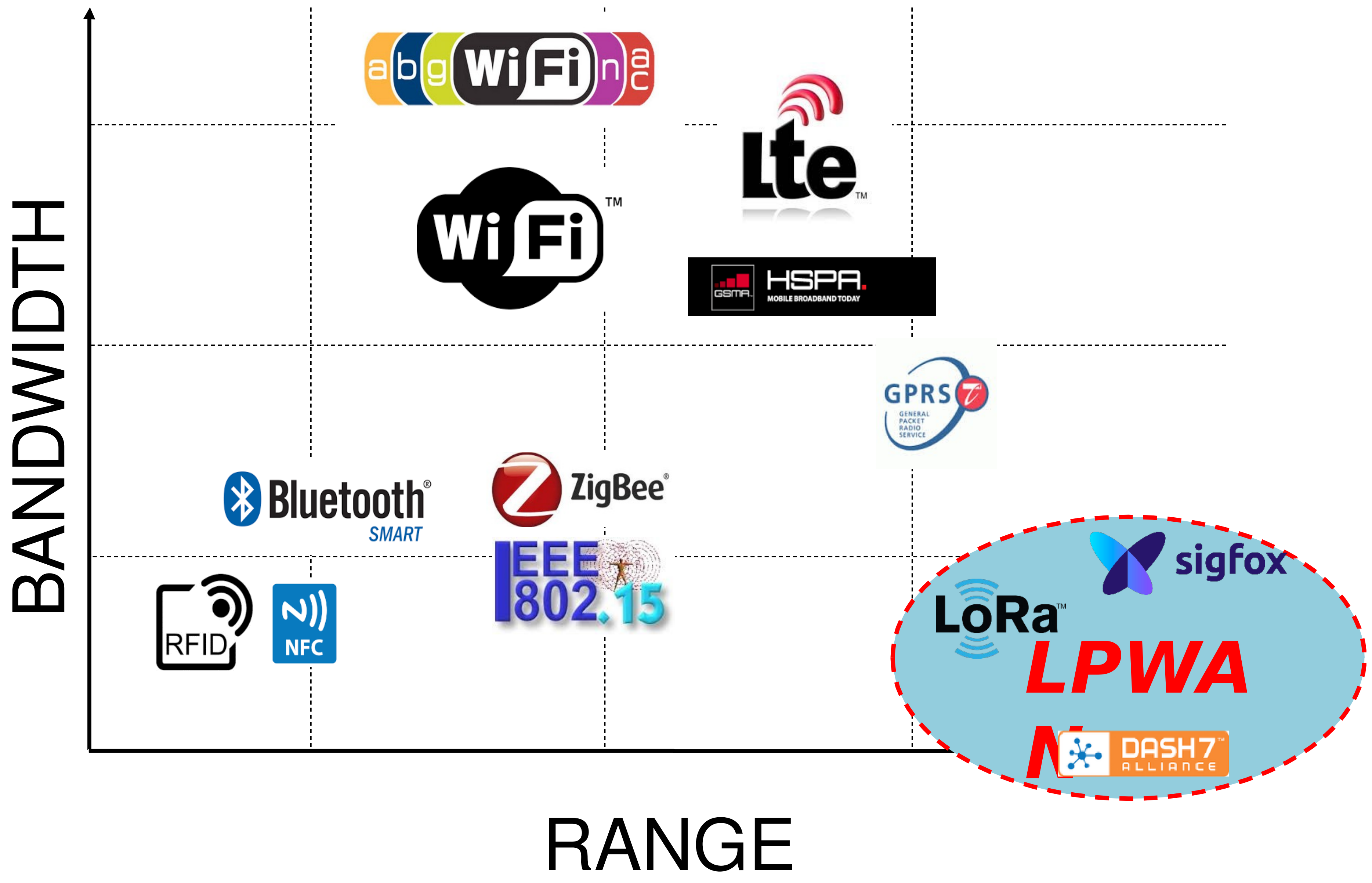
Wireless communication:

- Low power: long battery life
- Long range: big pastures
- Low data rates: telemetry
- Low cost: inexpensive system
- Scale: herds with 100s of animals

LPWANs:

Low Power Wide Area Networks

LOW POWER WIDE AREA NETWORKS (LPWAN)



LPWAN features:

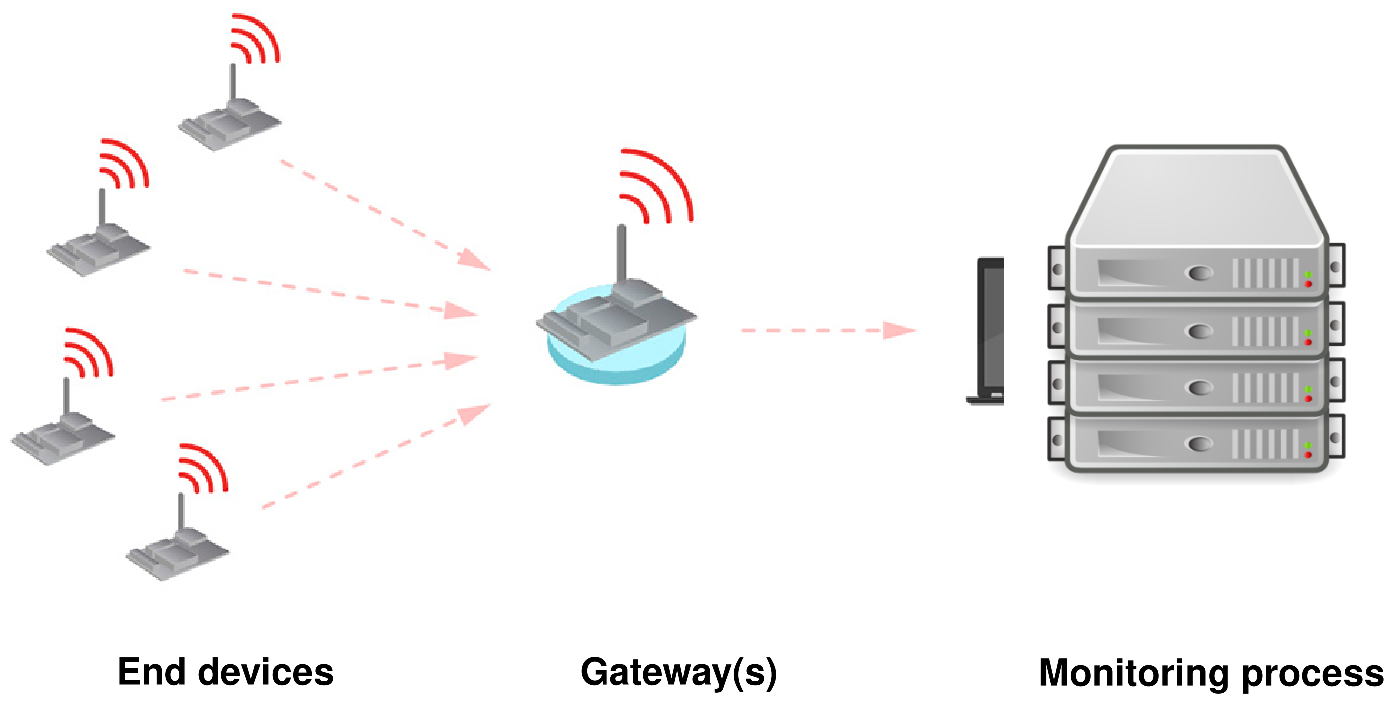
- Low power
- Low data rate
- Long range
- Scales (?)
- **Unlicensed spectrum**

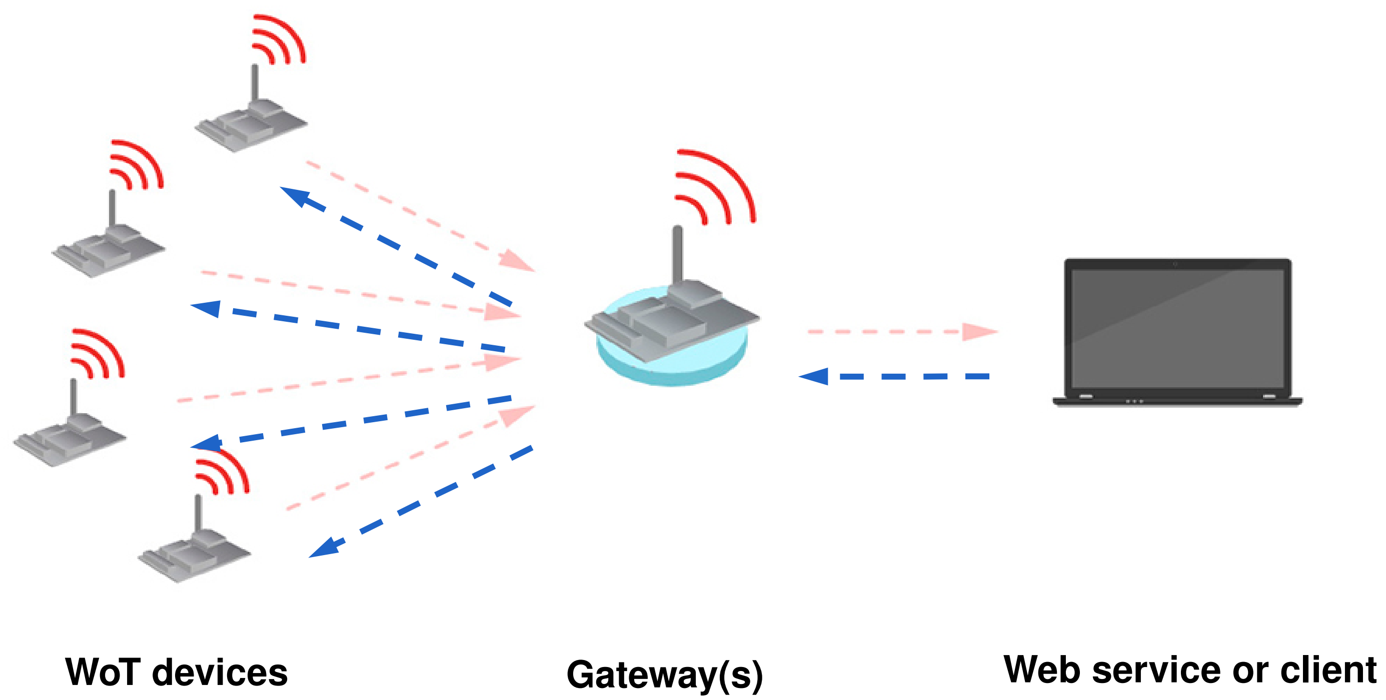
Regulatory restrictions on air time:

e.g. 0.1%, 1% or 10% Radio Duty Cycle time

0.36 3.6 36 seconds TX per hour

THE WEB OF THINGS IS COMING TO LPWANS





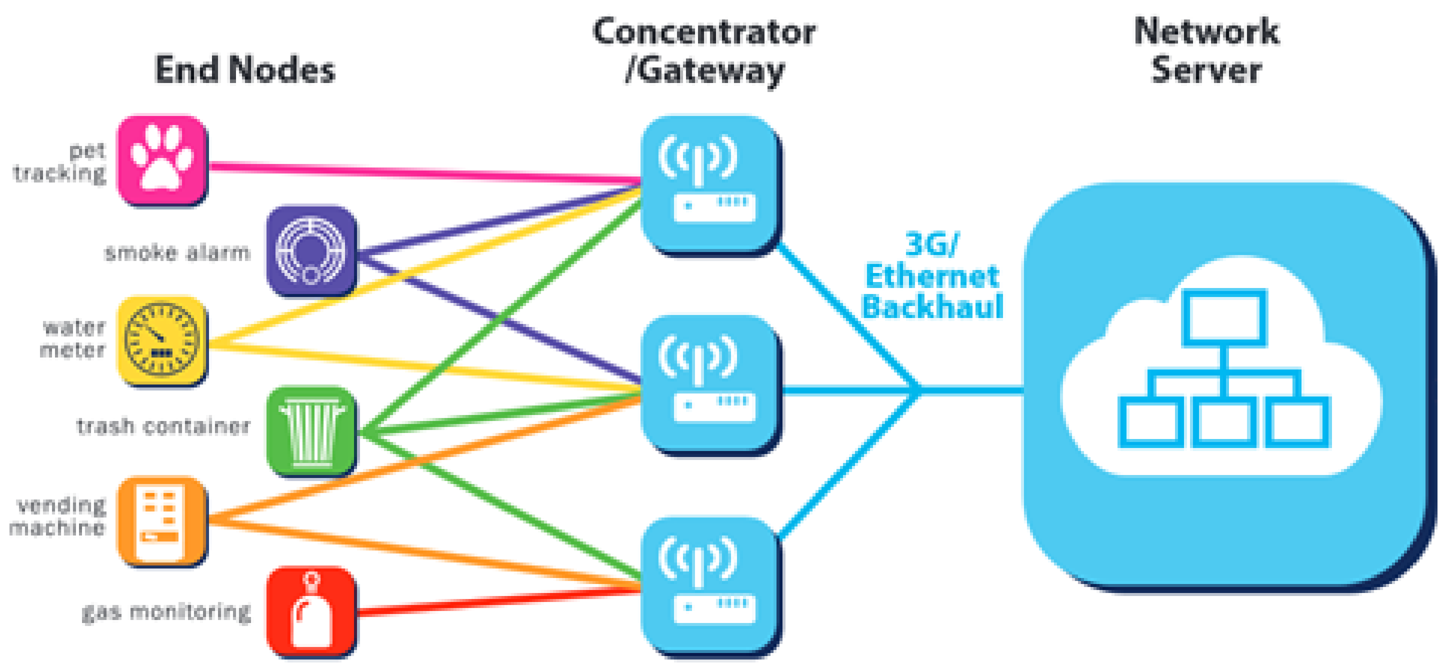
The IETF is bringing the WoT to LPWANs, BUT:

- LPWANs focus on upstream traffic.
- RDC limitations as a new constraint

Are prior results applicable to LoRaWAN?

- Request/response model of CoRE in LoRaWAN?
  - Bidirectional traffic: up AND downstream messages
  - Impact on scalability: hundreds, thousands of end devices per gateway.
- Existing studies did not consider downstream traffic.

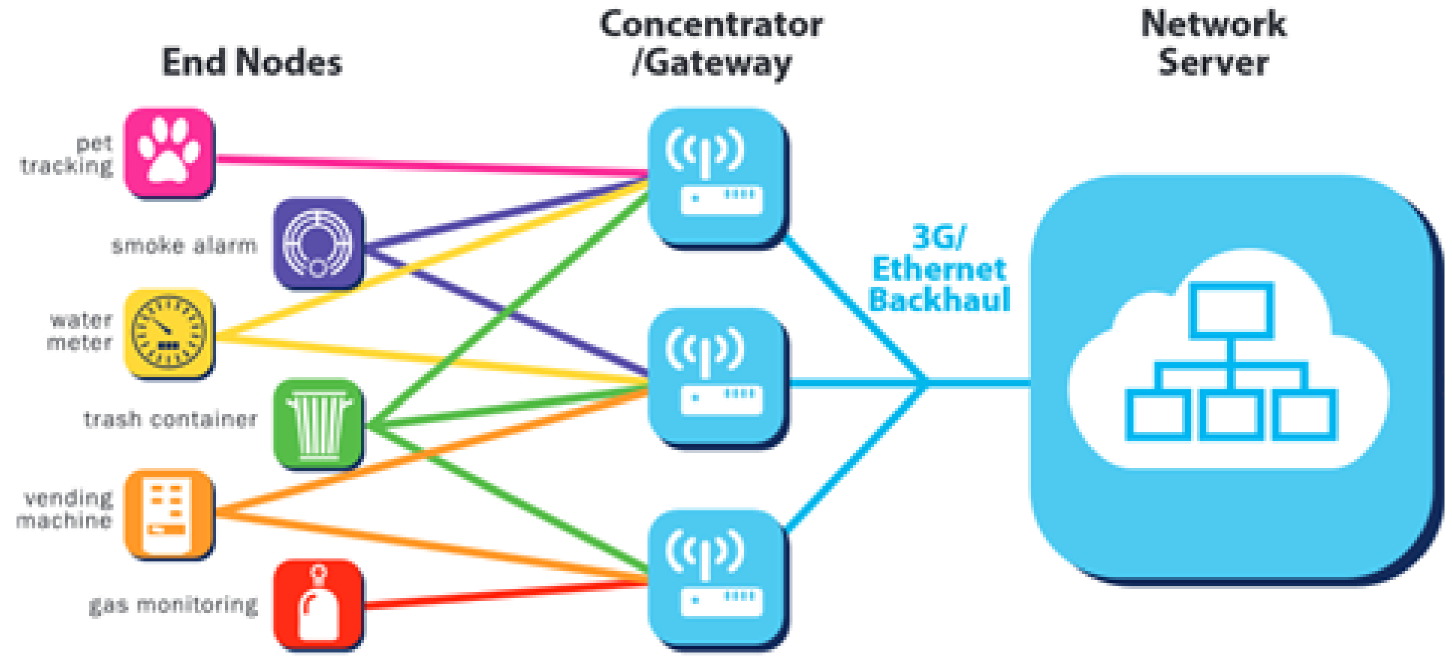
LORAWAN SCALABILITY STUDY IN NS-3



Modeled LoRaWAN in ns-3 and studied impact of:

- Assigning data rates to end devices
- Unconfirmed vs confirmed messages
- Impact of more than one gateway

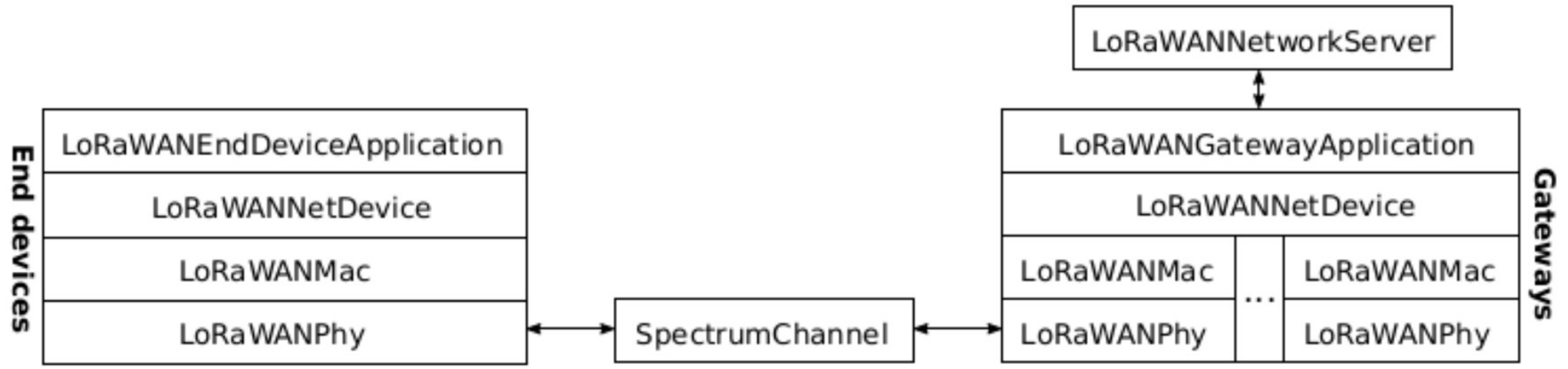
LORAWAN SCALABILITY STUDY IN NS-3

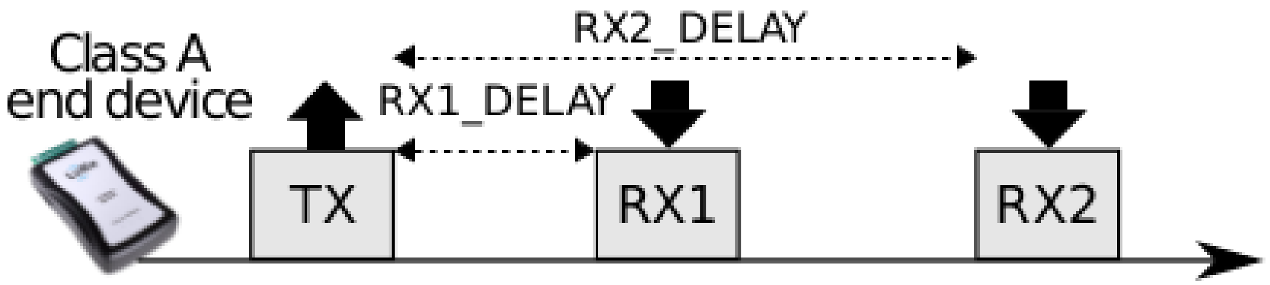


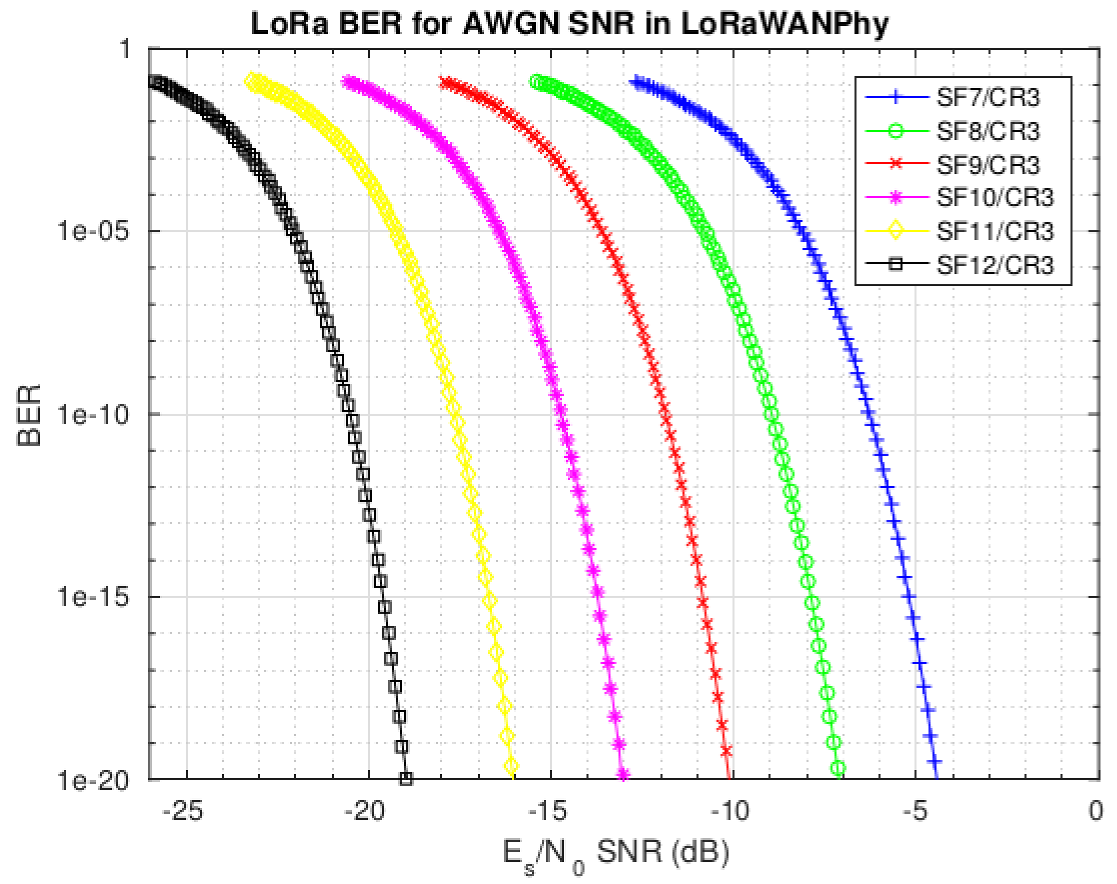
Modeled LoRaWAN in ns-3 and studied impact of:

- Assigning data rates to end devices
- Unconfirmed vs confirmed messages
- Impact of more than one gateway

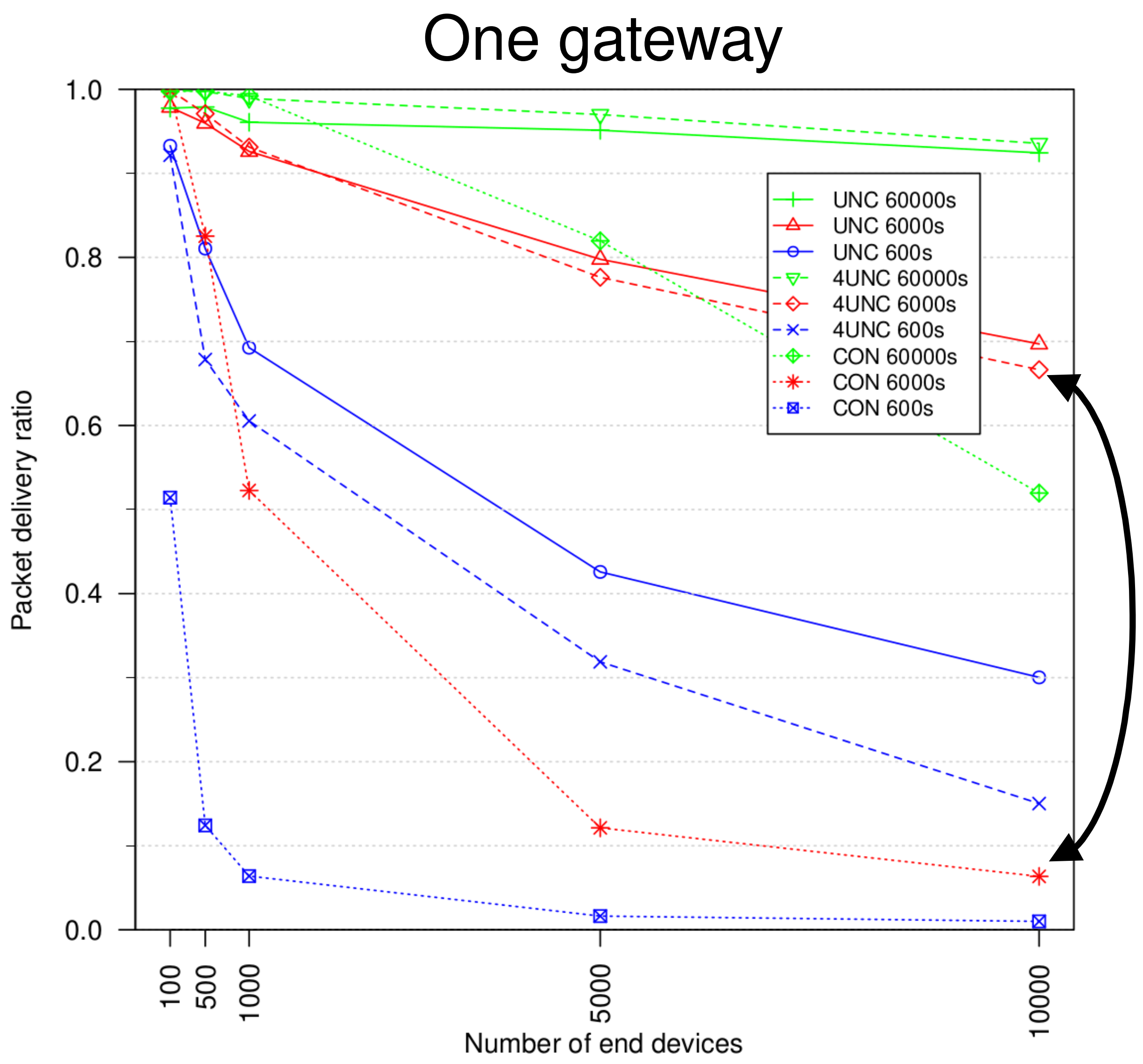
Modeling the physical and MAC layer of LoRaWAN in ns-3:





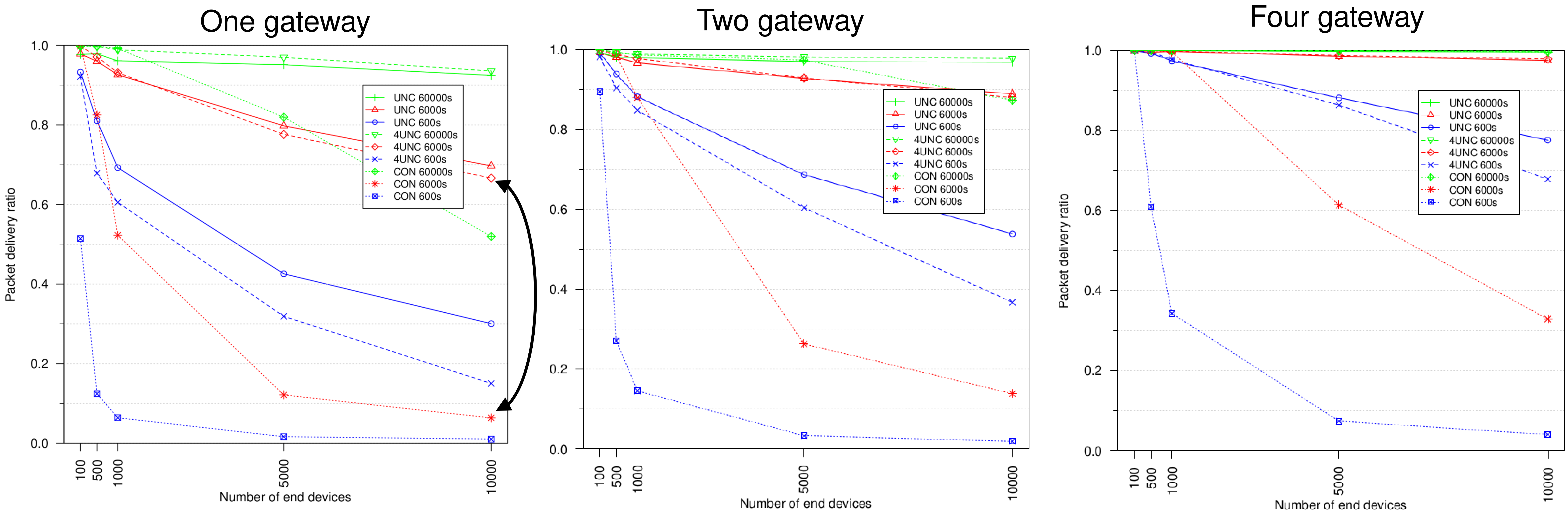


IMPACT OF BIDIRECTIONAL TRAFFIC?



Packet Delivery Ratio for bidirectional traffic is significantly lower.
Caused by **Radio Duty Cycle limitations** for gateways.
Absence of acknowledgments leads to retransmissions which increases interference.

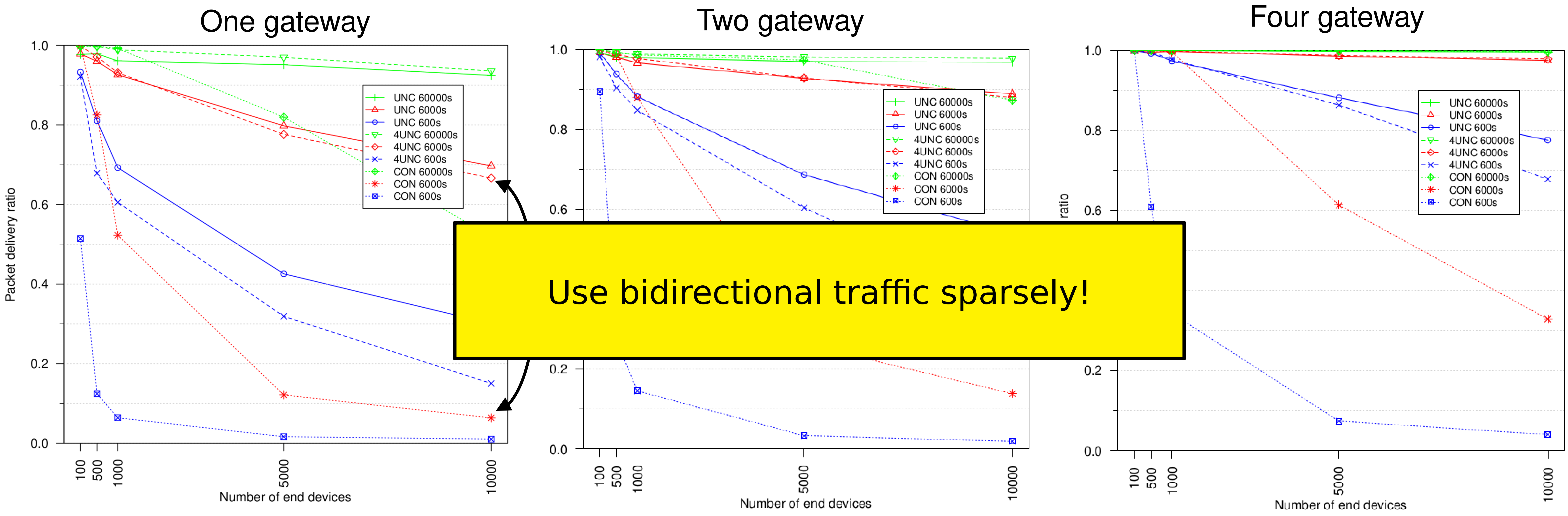
IMPACT OF BIDIRECTIONAL TRAFFIC?



PDR for bidirectional traffic is significantly lower.
Caused by Radio Duty Cycle limitations for gateways.

As gateway density grows, the impact of the RDC limitations is reduced and the PDR increases.

IMPACT OF BIDIRECTIONAL TRAFFIC?



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As gateway density grows, the impact of the RDC limitations is reduced and the PDR increases.

5. SUMMARY

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SUMMARY

- The Internet will become ubiquitous.
  - *“The Internet will disappear”* – E. Schmidt
  - “*Software eats the world*, *as everything gets connected”*
- The Internet of Things will be diverse and will need to interoperate.
- This dissertation researched how **Distributed Intelligence** and **Sensor Function Virtualization** can aid the integration of the resource-constrained Web of Things into applications and services.
- This work contributed towards the goal of an open and secure WoT, where many heterogeneous devices co-exist and interoperate.

FACULTY OF ENGINEERING
AND ARCHITECTURE

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