Pascal Thubert

# Bringing determinism in wireless Networks for IoT

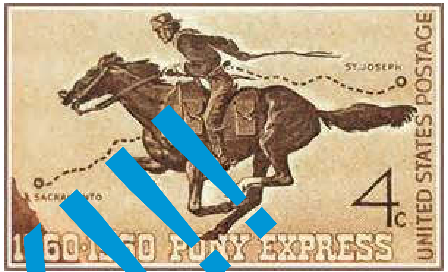
Global IOT Submit 2018, Bilbao

June 2018

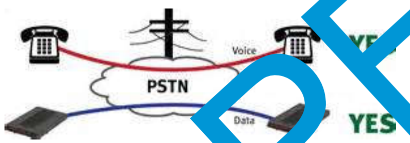
# Converging on IP => lower cost + distinct new Value

OPEX!!!

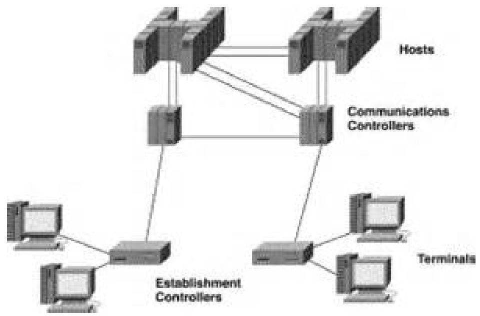
- Mail: slow, insecure




- Telephone: expensive for long distance




- TV: low quality, conflicting standards dedicated sets


- Data networks: limited

- email: free, high volumes, archives
- Skype, Webex: free, brings video and conferencing
- Netflix: on-demand, on-the-move, interactive/participative
- Internet: new breed of devices, for a new economy

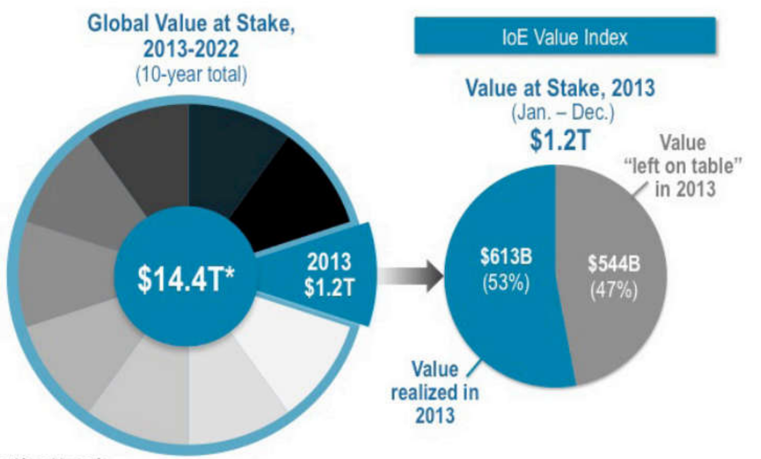
# The Industrial Internet of Things

## Converge Control Networks to IP

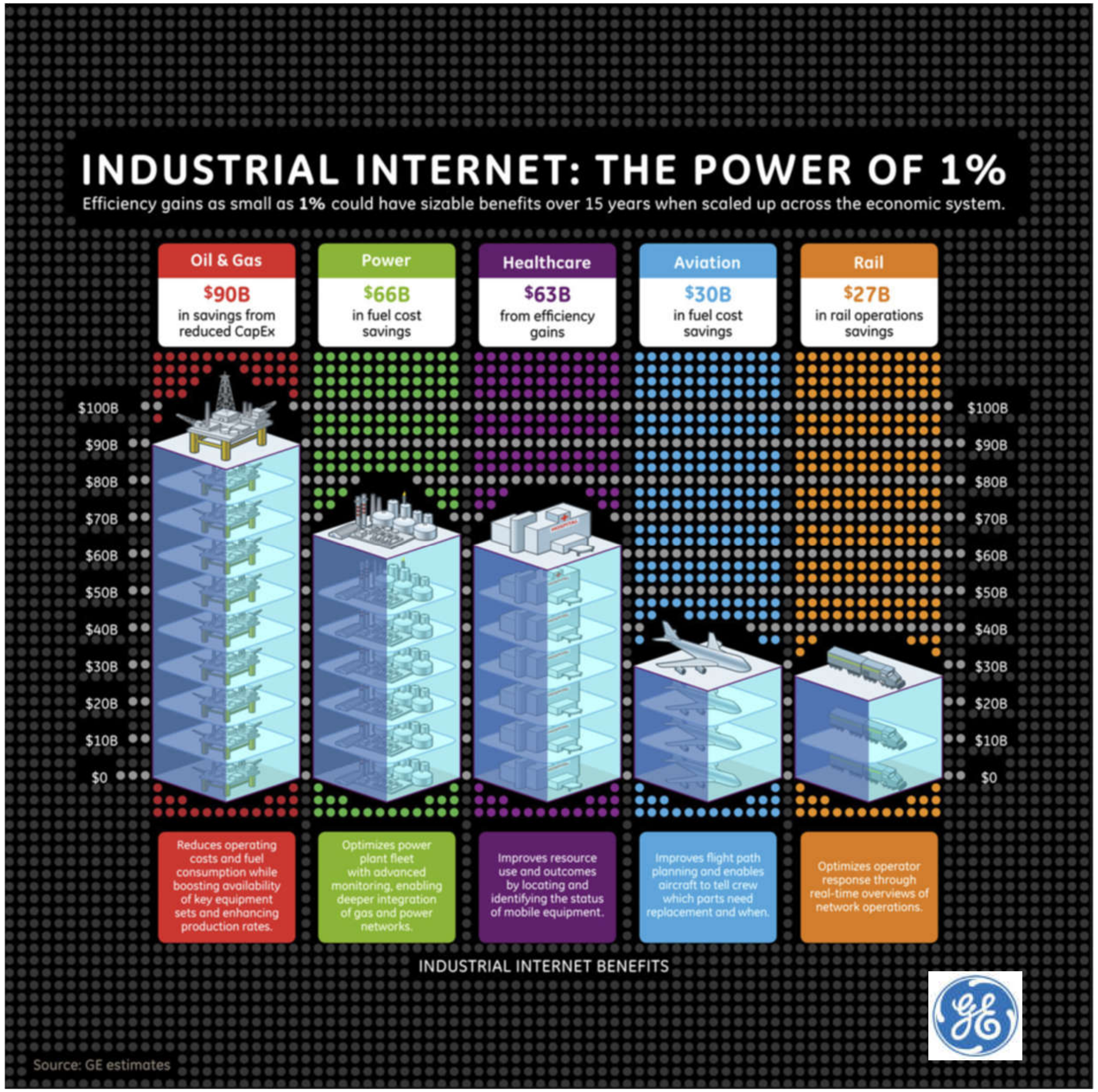
- Make IP operations more efficient
- Emulating existing Industrial protocols

## Beyond Control and Automation

- Optimize processes (by 1%?)
- Leveraging IT, Live big data and Analytics




Note: chart is not to scale
* $14.4T is conservative because it is based on a set number (21) of private-sector use cases and discounts future cash flows due to uncertainty around privacy and regulatory issues.



# Networking in Operational Technology

## Control loops and Movement detection

Deterministic: highly reliable, fixed latency, global optimization through central computation.

with static multipath, packet replication and elimination at the edges (PRP, HSR).

## Large Scale Monitoring

Stochastic: self-healing - thus distributed routing (RPL)

Background resource optimization

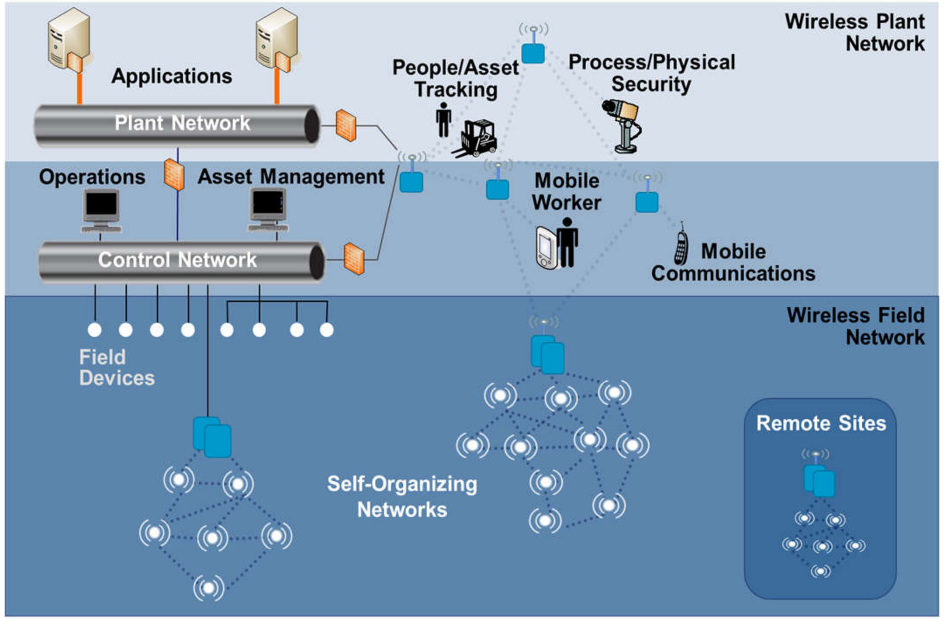
## Management

a separate topology that does not break.

## alerts

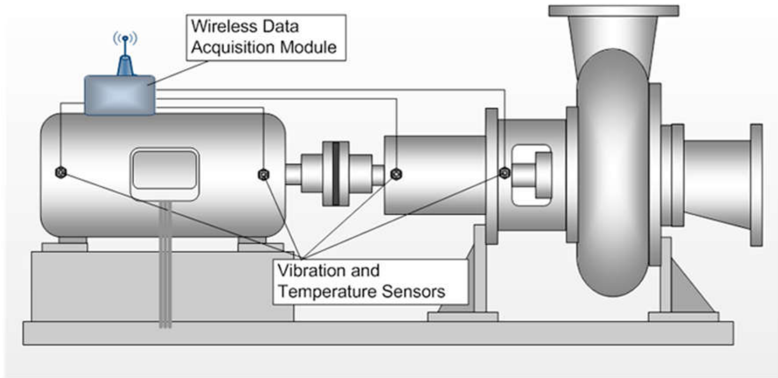
bursty, unexpected, on-demand slot allocation, prioritization

Dynamic resource optimization



# Condition Monitoring and Large Scale Monitoring

- Not Process Control but “Missing Measurements”
  - Reliability and availability are important, which implies
  - Scheduling and admission control
- Scalability
  - 10’s of thousands of new devices
- Deployment cost factor is key



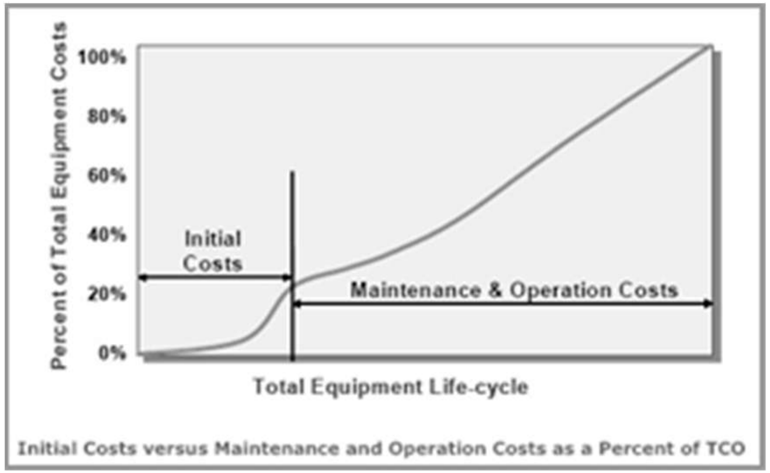


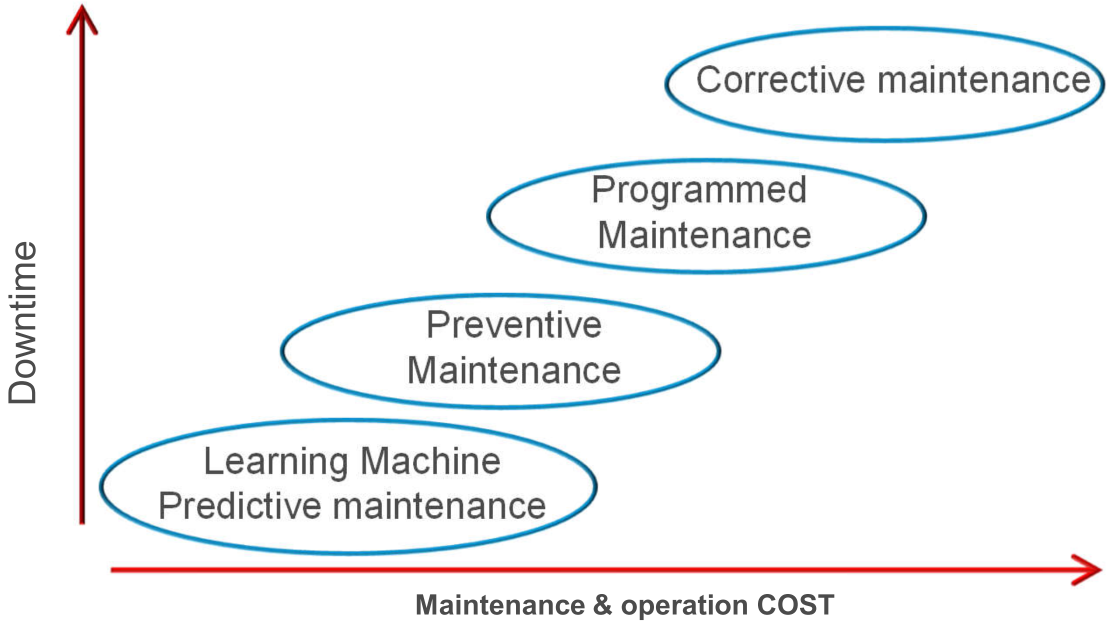
For Emerson this is the **second layer of automation**:

Typically missing are the measurements you need to monitor the condition of the equipment--temperature, pressure, flow and vibration readings you can use to improve site safety, prevent outages and product losses, and reduce maintenance costs of equipment such as pumps, heat exchangers, cooling towers, steam traps and relief valves.

# Industry objective: Reduce OPEX

- Maintenance and operation cost represent 75% of the Total equipment cost




➔ Deployment of Wireless sensors is seen as an efficient way to achieve it

# DETERMINISTIC NETWORKING

# What is Deterministic?

(per Wiki

I know what, I control when, I can reproduce it every time, guaranteed

In mathematics and physics, a det … randomness is
involved in the development … istic model will thus always
produ … condition or initial state.
[In philo … ptual model of the philosophical doctrine of
determi … erstanding everything that has and will occur in the
system, ba … tcomes of causality. In a deterministic system, every action, or
cause, … action, or effect, and every reaction, in turn, becomes the cause of
subsequent … tions. The totality of these cascading events can theoretically show exactly how
the system will exist at any moment in time.

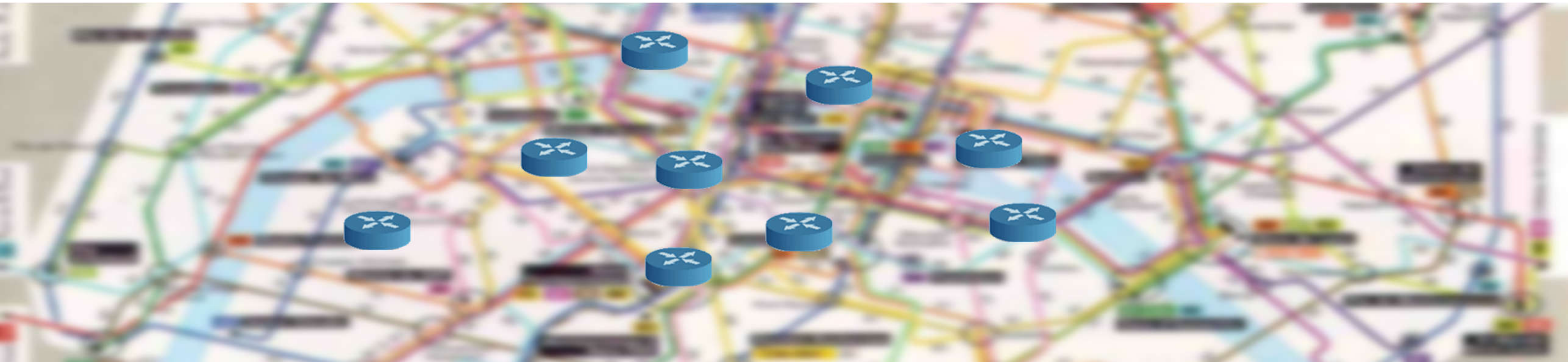
# The bus analogy (to deterministic circuit switching)

A bus every T. minutes => guaranteed latency max_wait + travel

Reserved bus lanes => no interaction with other traffic

Switching buses => Lower complexity but increased latency

<u>Towards a perfect emulation of a serial cable over a switched network</u>

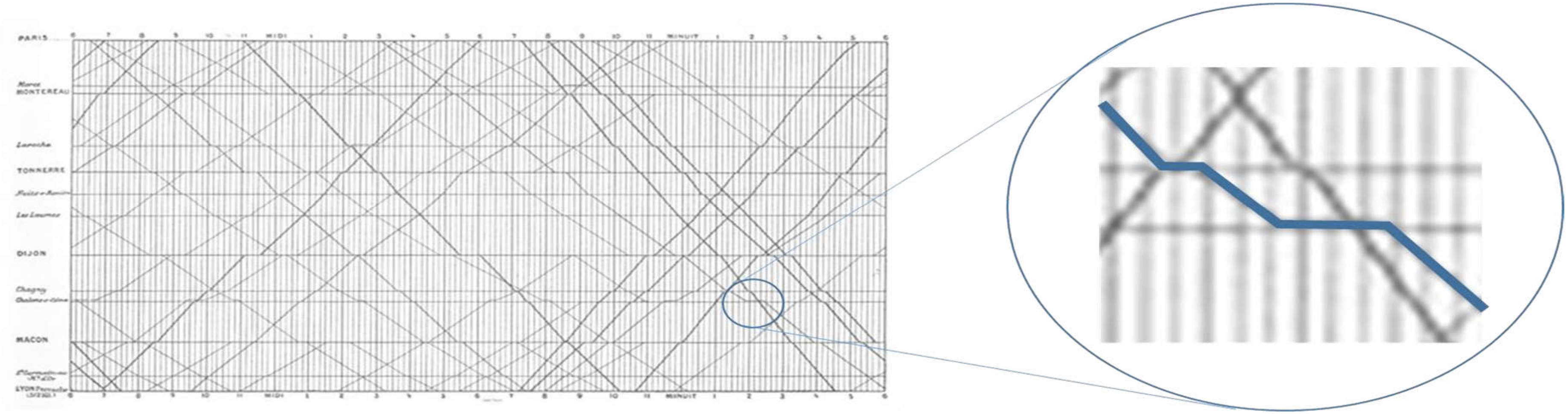


# The Train Analogy (to control loop traffic)

Periodic trains along a same path and same schedule (time table)

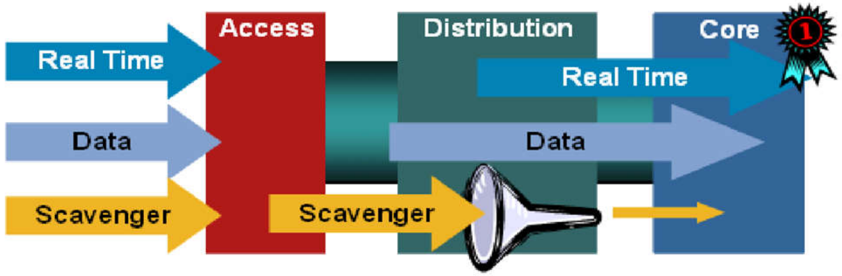
Collision avoidance on the rails guaranteed by schedule

End-to-End latency enforced by timed pause at station




<u>Typical deterministic flows incur a higher latency than “hot potato”</u>

# The casino analogy (to statistical effects)




The Law of large numbers says:

Long term, the casino **will** win.

Long term, for any value of *X*, some player will win **more** than *X*.

That's in theory an unbounded peak

The object of DetNet is to remove chance from the picture.

We have always been in the business of optimizing average throughput and latency. (The law of large numbers.)

=> A deterministic flow must traverse the network in the same predictable fashion every time, regardless of the load of the network.

# Benefits of scheduling in wired networks

- Eliminate congestion loss
  - ⇒ Controlled amount of traffic
  - ⇒ Available Resources (bandwidth and buffers) guaranteed
- Guarantee latency
  - ⇒ Deterministic Progress along Scheduled path
  - ⇒ Nor ARQ: Forward Error correction, Network coding
- (Nearly) Eliminate equipment failure losses
  - ⇒ Frame/Packet Replication and Elimination

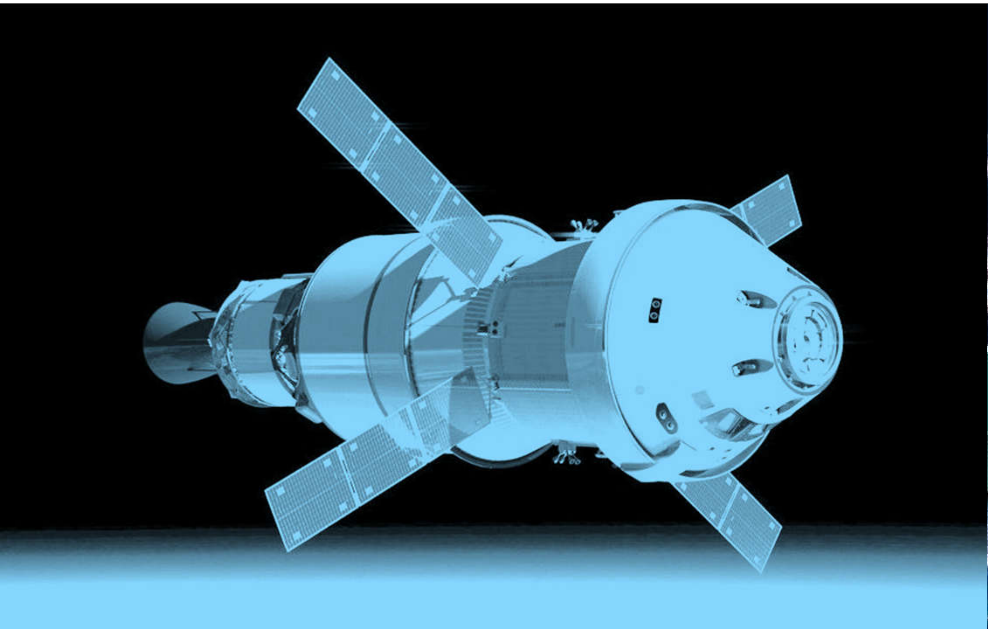
# Key Take Aways on Deterministic Networking

**Scheduling and Perfect timing** for an optimum use of the medium.

**Low loss / Hard bound latency.** A new level of QoS guarantees for IT.

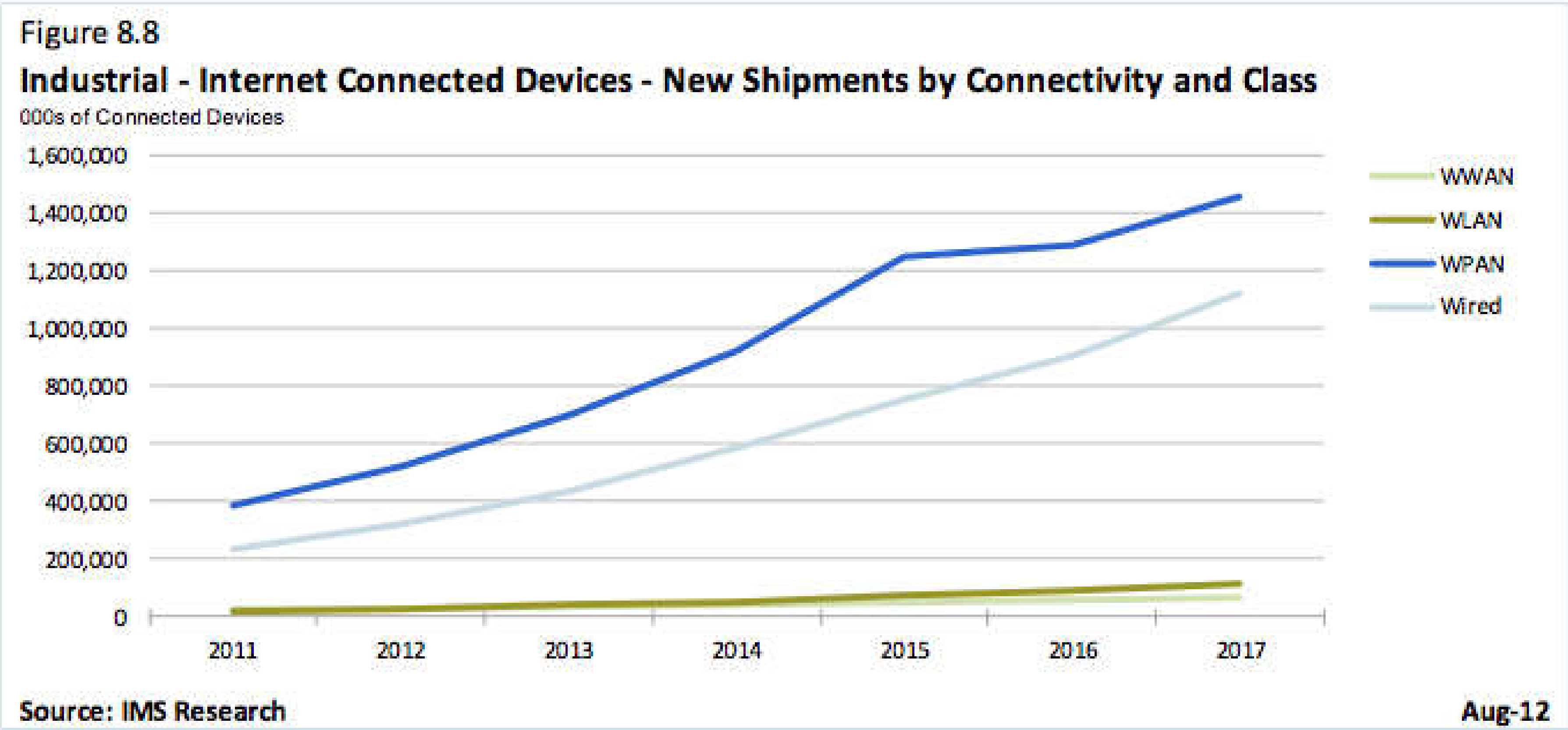
**Sharing physical resources** with classical best effort networking.

**High ratio of critical flows** for traffic known a priori.



# MAKING WIRELESS MORE PREDICTABLE

# Industrial connected device growth



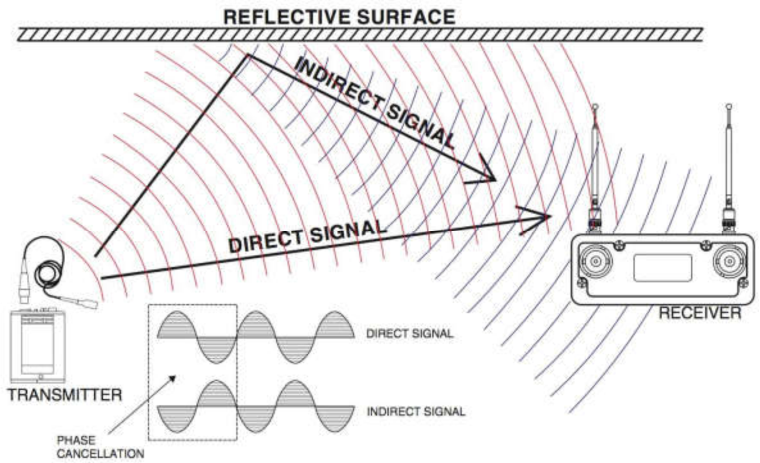

WWAN: GSM – LTE WLAN: 802.11 WPAN: 802.15.4, ISA100.11a, WirelessHART

# Benefits of scheduling in wireless

- Reduces **frame loss**
  - ⇒ Time and Frequency Diversity
  - ⇒ Reduces co-channel interference
- Optimizes **bandwidth usage**
  - ⇒ No blanks due to IFS and CSMA-CA exponential backoff
  - ⇒ While Increasing the ratio of guaranteed critical traffic
- Saves **energy**
  - ⇒ Synchronizes sender and listener
  - ⇒ Thus optimizes sleeping periods
  - ⇒ By avoiding idle listening and long preambles

# Very High Probability Wireless

- Controlling time of emission
  - Can achieve ~10μs sync on 802.15.4
  - <u>Can guarantee time of delivery</u>
- Protection the medium
  - ISM band crowded, no fully controlled
  - all sorts of interferences, including self
  - <u>Can not guarantee delivery ratio</u>
- Improving the Delivery ratio
  - Different interferers => different mitigations
  - <u>Diversity is the key</u>



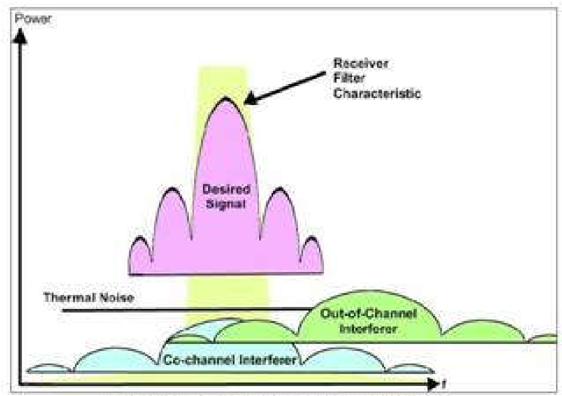




Figure 1. Co-Channel, Adjacent Interference, and Thermal Noise
All signals are referenced to zero power level.

# Diversity in Wireless


## Code diversity

- Code Division Multiplex Access
- Network Coding (WIP)

## Frequency diversity

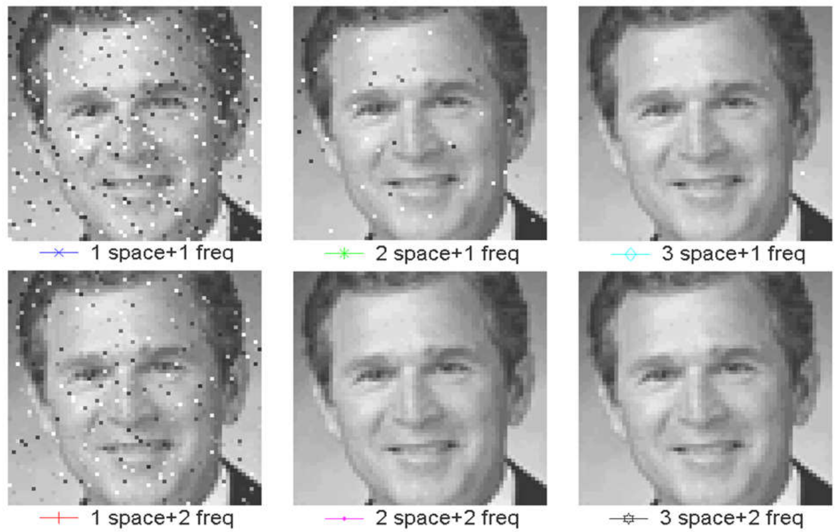
- Channel hopping
- B/W listing

## Time Diversity

- ARQ + FEC (HARQ)
- TDM Time slots

## Spatial diversity

- Dynamic Power Control
- DAG routing topology + ARCs
- Duo/Bi-casting (live-live)




**Use all you can!**

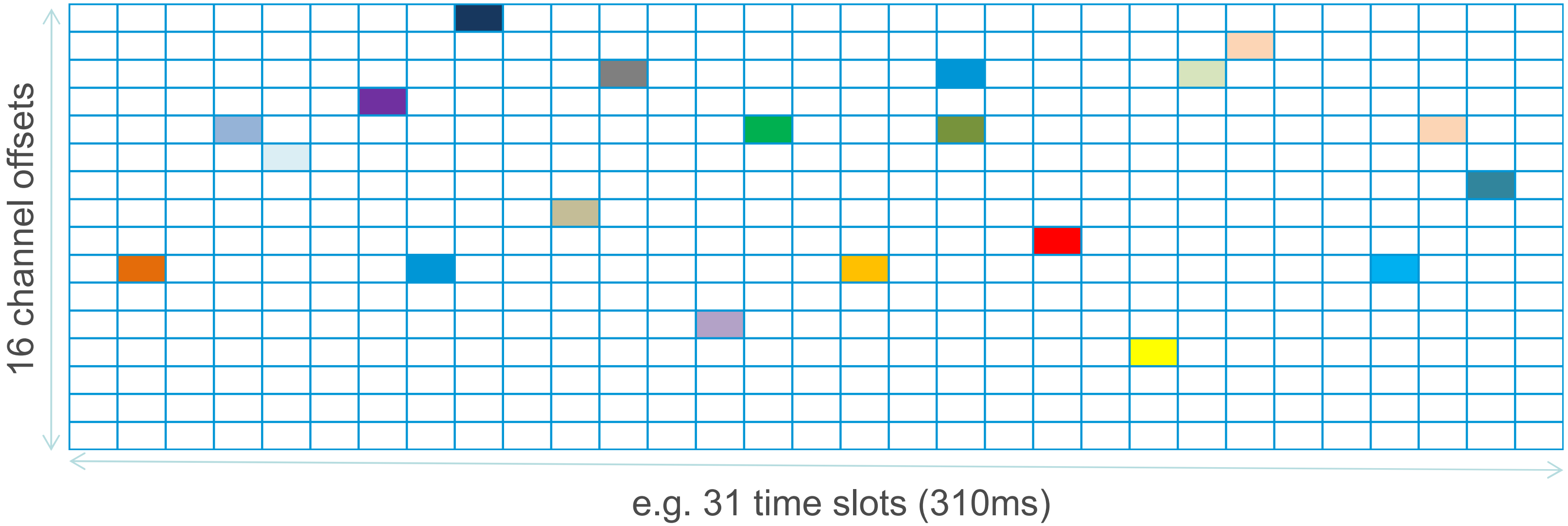
# So how do we make wireless deterministic?

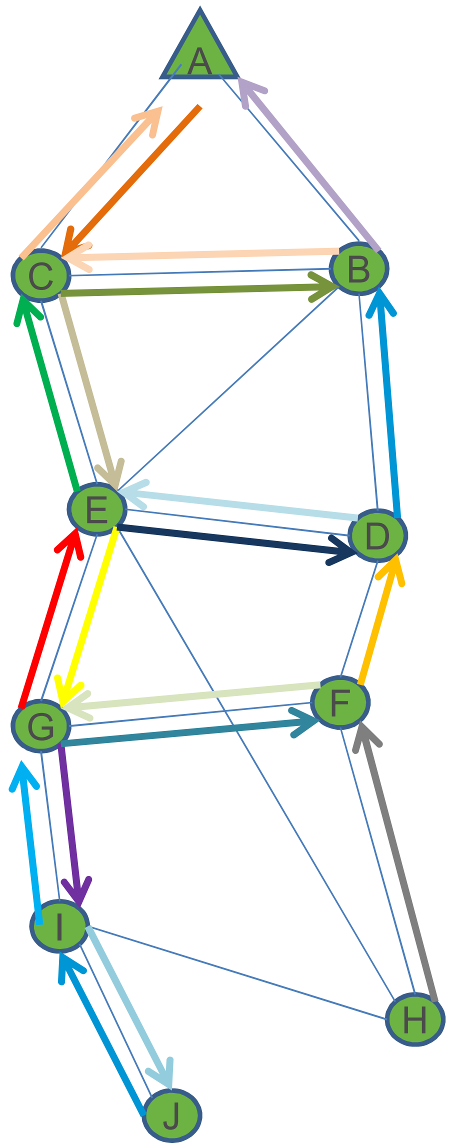
**Schedule** every transmission (they all do it!)

to maintain the medium free at critical times

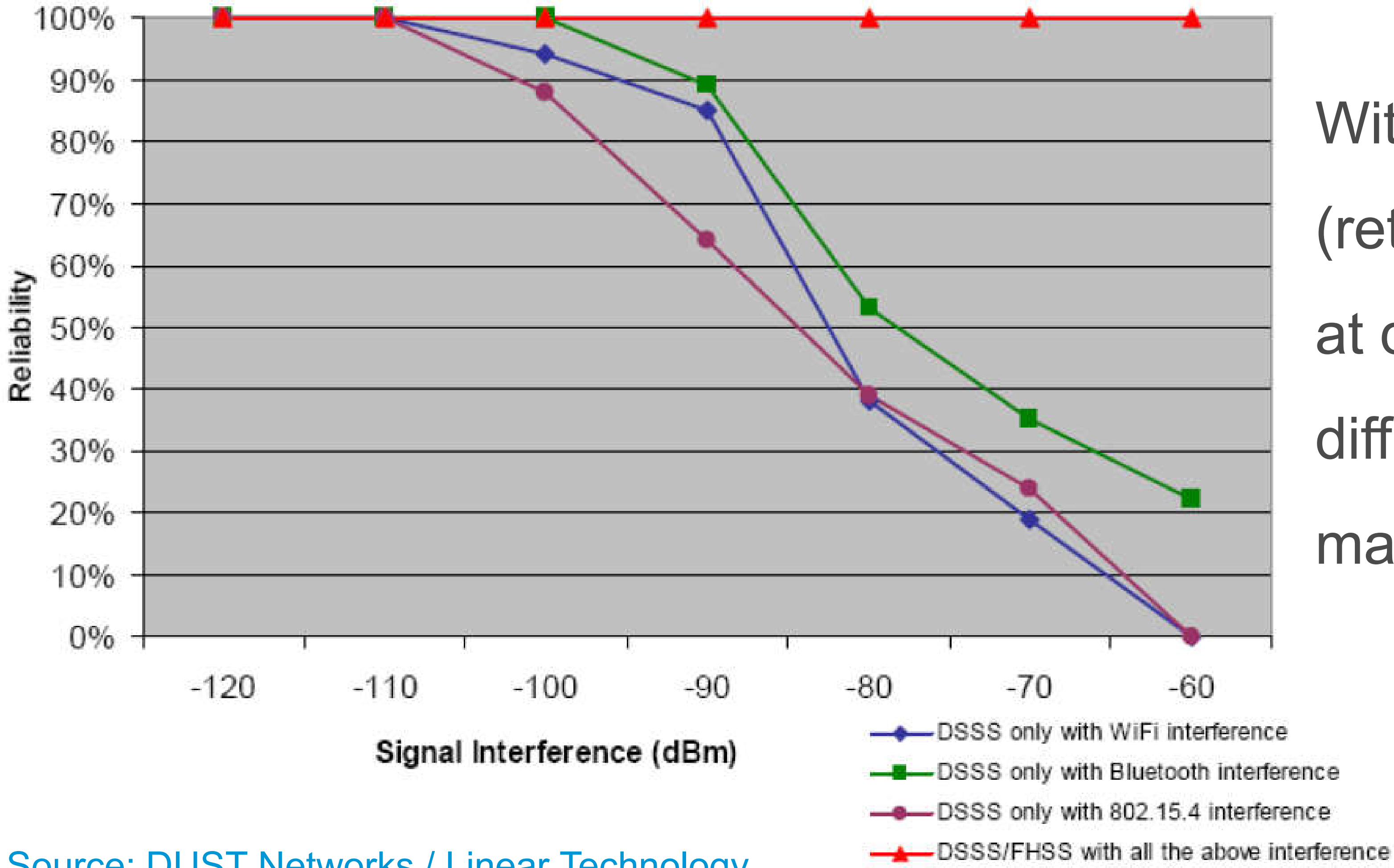
e.g. T+FDM with CG-Mesh, and TimeSlotted Channel Hopping (TSCH)

TSCH is used in WirelessHART, ISA100.11a, and is the base for **6TiSCH**



# Frequency hopping vs. DSSS in 802.15.4 Networks




With TSCH, ARQ (retries) are scheduled at different times over different channels to maximize diversity.

Source: DUST Networks / Linear Technology

# Key take-aways on deterministic wireless

## Wireless can be made Deterministic through TDM and Scheduling

### Provides similar benefits as wired

⇒ High delivery ratio through path redundancy and collision elimination

⇒ High ratio of critical flows

⇒ Bounded maximum latency (and jitter)

### Centrally scheduled operations bring additional benefits in wireless

⇒ Medium usage optimization (no IFS, backoff, etc…)

⇒ Energy savings (wake up on scheduled transmission)

### But **how that is effectively achieved is different** in wireless

⇒ All transmission opportunities **MUST** be scheduled (not just deterministic ones)

⇒ Reserved scheduled transmission opportunities for critical traffic

⇒ Shared scheduled transmission opportunities & dynamic allocation for best effort

# Enters 6TiSCH

# TSCH: a versatile technology

Low Power **TSCH mesh** is a complex technology adapted to:

- Mesh: Range extension with **Spatial reuse** of the spectrum
- **IPv6-based Industrial Internet**
  - ⇒ Stochastic routing for large scale monitoring (RPL)
  - ⇒ Separation of resources between deterministic and stochastic (TSCH)
  - ⇒ Leveraging IEEE/IETF standards (802.15.4, 6LoWPAN …)
- Centralized optimization for **Deterministic flows**
  - ⇒ Mission-critical data streams (control loops)
  - ⇒ Reach Back to Fog deterministically for virtualized loops
  - ⇒ And limitations (mobility, scalability)

# 6TiSCH Scope

- Radio Mesh: Range extension with **Spatial reuse** of the spectrum
- TSCH with Centralized routing, optimized for **Time-Sensitive flows**
  - ⇒ Mission-critical data streams (control loops)
  - ⇒ Deterministic reach back to Fog for virtualized loops
  - ⇒ And limitations (mobility, scalability)
- RPL Distributed Routing and scheduling for large scale monitoring
  - ⇒ Enabling co-existence with **IPv6-based Industrial Internet**
  - ⇒ Separation of resources between deterministic and stochastic

  Leveraging IEEE/IETF standards (802.15.4, 6LoWPAN …)

# 6TiSCH WG Charter

**IPv6 over IEEE802.15.4 TimeSlotted Channel Hopping (6TiSCH)**

The Working Group will focus on enabling IPv6 over the TSCH mode of the IEEE802.15.4 standard. The scope of the WG includes one or more LLNs, each one connected to a backbone through one or more LLN Border Routers (LBRs).

**6TiSCH also specifies an IPv6-over-foo for 802.15.4 TSCH**

but does not update 6LoWPAN (that's pushed to 6lo).

Rather 6TiSCH defines the missing Data Link Layer.

**The 6TiSCH architecture defines the Layer-3 operation.**

It incorporates 6LoWPAN but also

RPL, DetNet (PCE) for deterministic networking,

COMAN, SACM, CoAP, DICE …

=> Mostly NOT specific to 802.15.4 TSCH

# 6TiSCH WG

Active IETF WG, 5 active WG docs, 1 in IESG review, 2 RFCs

Focusses on IPv6 Best effort traffic over TSCH

Applies / modifies existing standards
  (RPL, 6LoWPAN, OSCORE) over 802.15.4 TSCH

Defines an Architecture that links it all together

Fill gaps at Layer-2 and 3: 6top sublayer for L3 interactions

Open source implementations (openWSN…) and PlugTests

Multiple companies and universities participating

# 6TiSCH WG deliveries

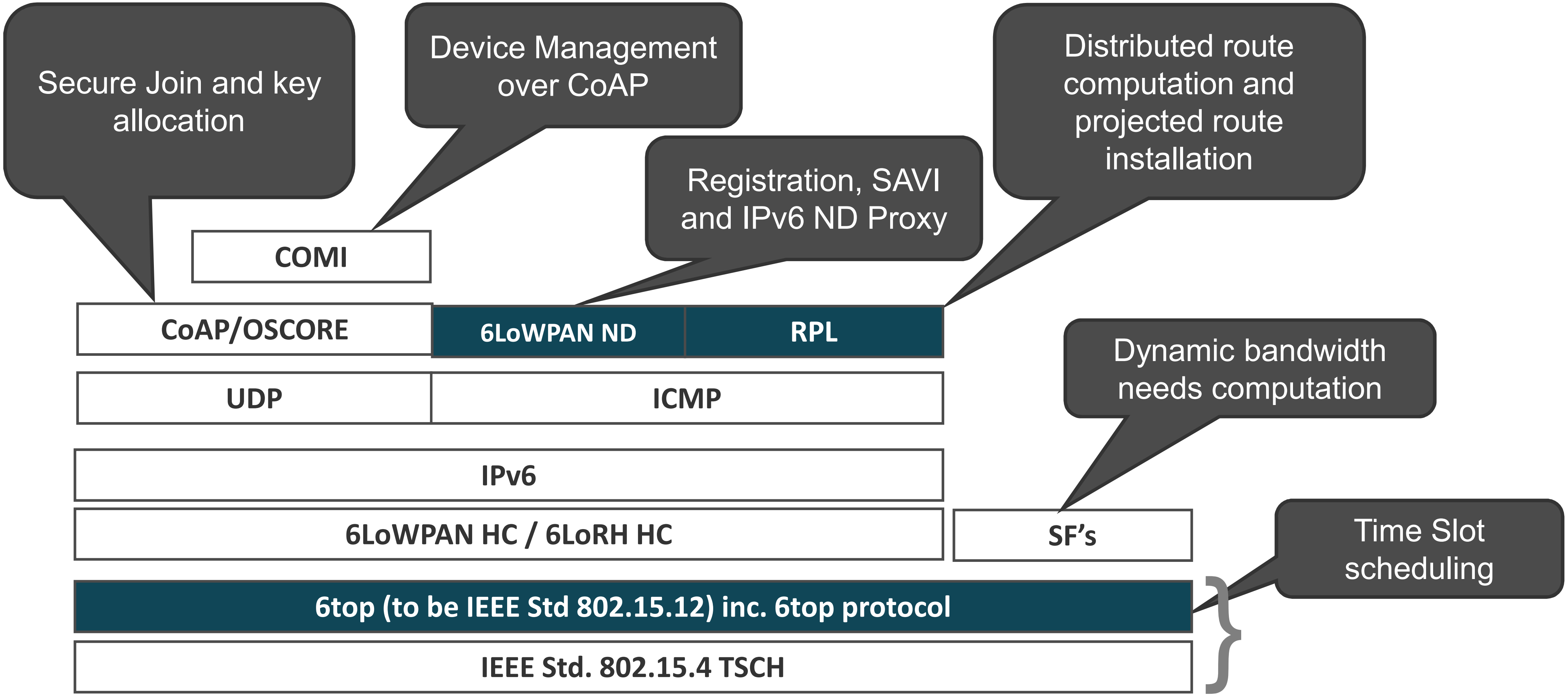
## 6TiSCH has to make components work together and push new work

- https://tools.ietf.org/html/draft-ietf-6lo-backbone-router
- https://tools.ietf.org/html/draft-ietf-6lo-rfc6775-update
- https://tools.ietf.org/html/draft-thubert-6lo-forwarding-fragments
- https://tools.ietf.org/html/draft-ietf-roll-dao-projection
- https://tools.ietf.org/html/rfc8025
- https://tools.ietf.org/html/rfc8138

## Active 6TiSCH drafts and RFCs

- https://tools.ietf.org/html/rfc7554
- https://tools.ietf.org/html/rfc8180
- https://tools.ietf.org/html/draft-ietf-6tisch-terminology
- https://tools.ietf.org/html/draft-ietf-6tisch-architecture
- https://tools.ietf.org/html/draft-chang-6tisch-msf
- https://tools.ietf.org/html/draft-ietf-6tisch-6top-protocol
- https://tools.ietf.org/html/draft-ietf-6tisch-minimal-security
- https://tools.ietf.org/html/draft-ietf-6tisch-dtsecurity-zerotouch-join

# 6TiSCH Client stack



# WHICH STANDARDS FOR THE INDUSTRIAL INTERNET ?

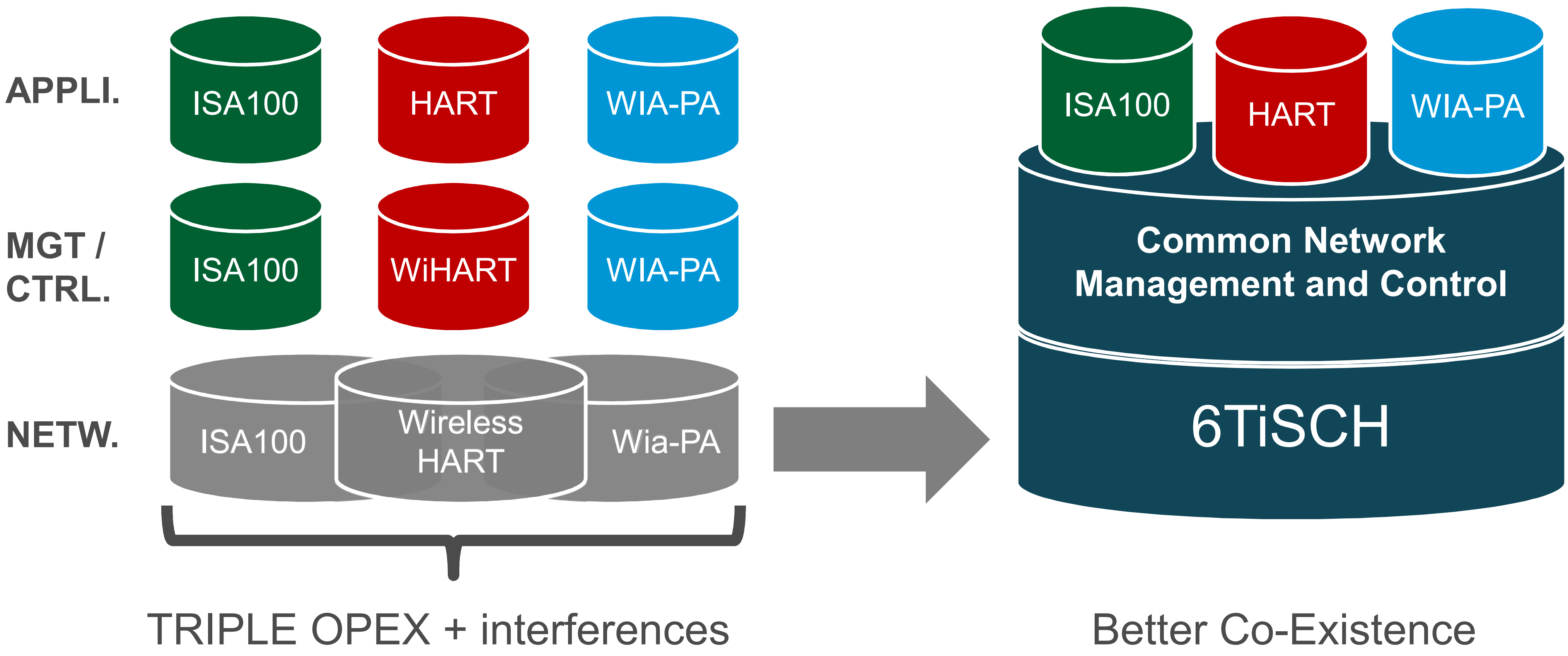
# Options for “Deterministic” radios

- Battery-operated and Scavenging
  - WirelessHART$^{TM}$, ISA100.11a – Silo’ed
  - 802.15.4 **TSCH** – and then TSCH over other PHYs
- Powered
  - 802.15.1 WISA (ABB) – Evolved into WSAN-FA,
  - 802.11 iPCF (Siemens) – Time Sliced but Proprietary
  - Other Wi-Fi evolutions
  - **U-LTE -** Going to IMS band opens a huge potential

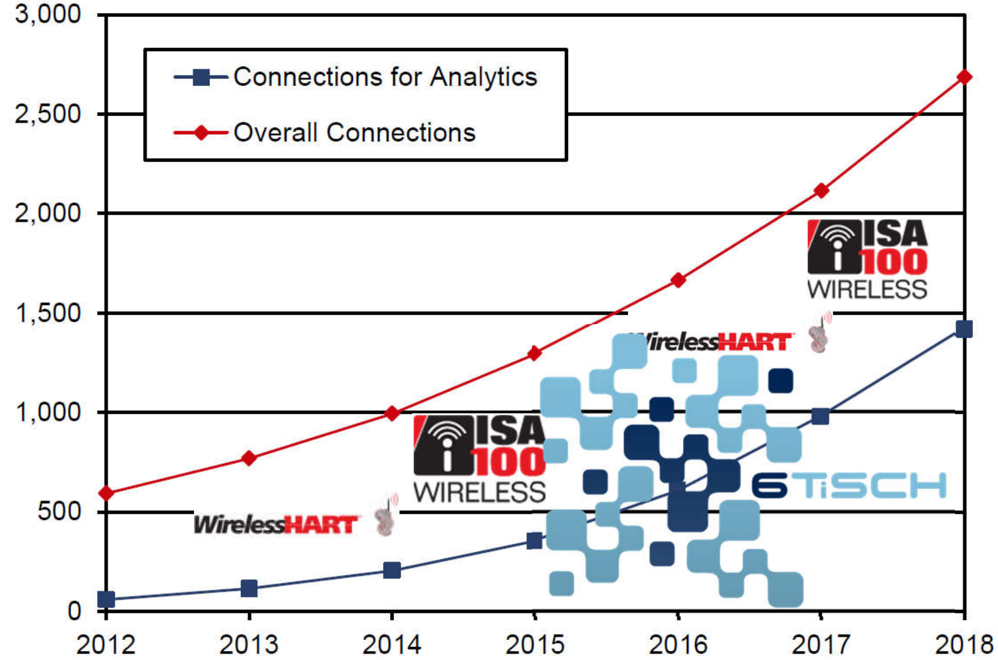
# Sharing the medium with stochastic IP

| Type of traffic / Type of MAC | **Deterministic (e.g. Control Loops)** | **Stochastic (e.g. classical IP)** |
| --- | --- | --- |
| **Deterministic (e.g. 802.15.4 TSCH)** | Good fit<br>Adapted to centralized routing and fully scheduled operation<br>**All industrial protocols are here** | **Difficult but achievable**: requires dynamic allocation of transmission resources (6TiSCH, ~CG-Mesh) |
| **Stochastic (e.g. Zigbee, Wi-Fi)** | Problems with channel access (guard time)<br>Lead to gross over-provisioning<br>CSMA **cannot provide hard guarantees** | Good fit<br>Adapted for **IP traffic, distributed routing** and statistical multiplexing with RED |

# Potential: Converged network and control



# What’s missing now?




Everything is centrally computed.

Mesh size usually limited to 10-100 nodes.

A distributed scheduling and routing is needed to enable large scale monitoring for **Industrial Internet** over the shared medium

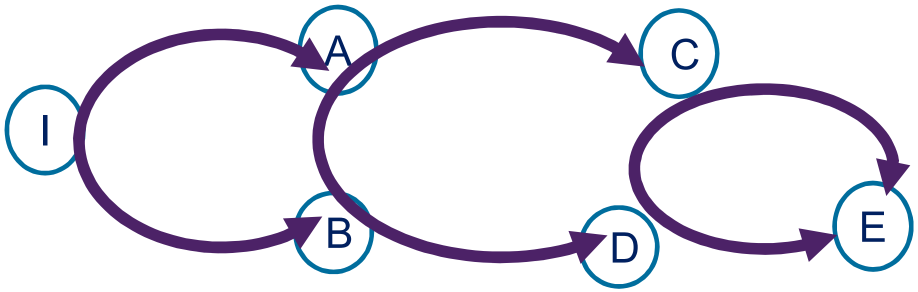
That’s what **6TiSCH** adds to the picture with possible coexistence

# Applying BIER and DetNet to 6TiSCH

# Core approach: leverage inherent radio properties

Radios are lossy, but they are also inherently broadcast:
Use that latter property as a compensation for the former

1. Multipath Tracks with the general shape of a cord ladder



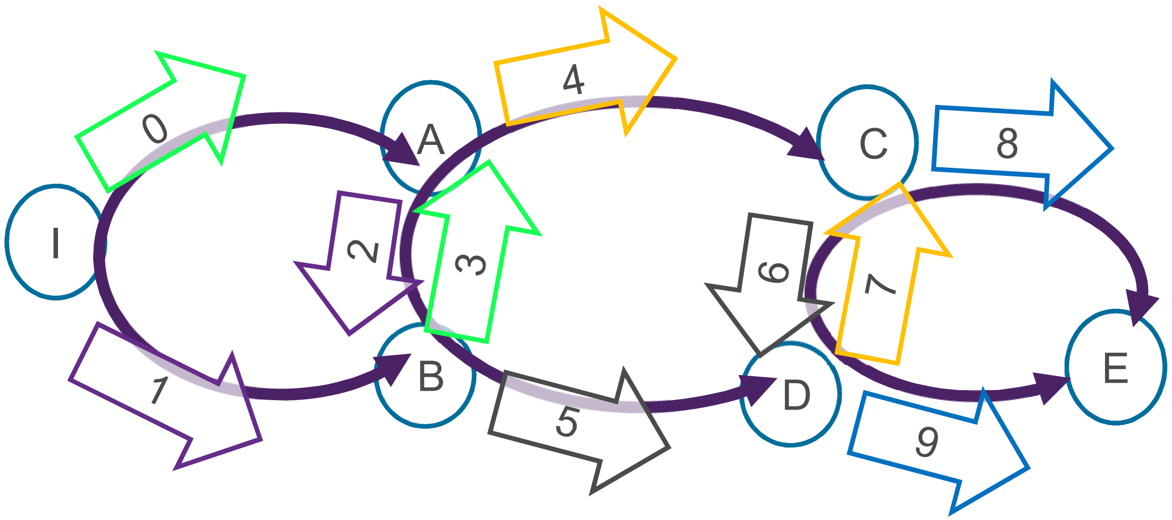

2. Control the replication and elimination to save energy
3. Use intelligent flooding leveraging broadcast properties

Goals: minimize energy, minimize latency, optimize delivery and avoid 4 losses in a row

# Test1: Flooding an ARC chain

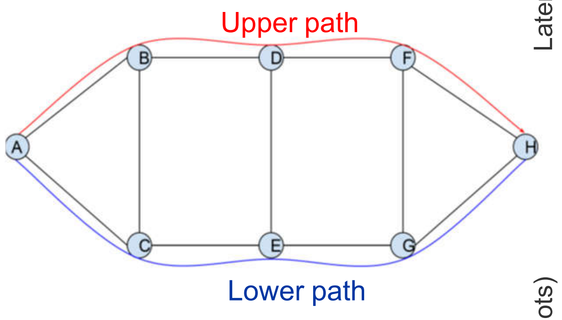
<u>Novelty: ARC chains, multipath scheduling</u>

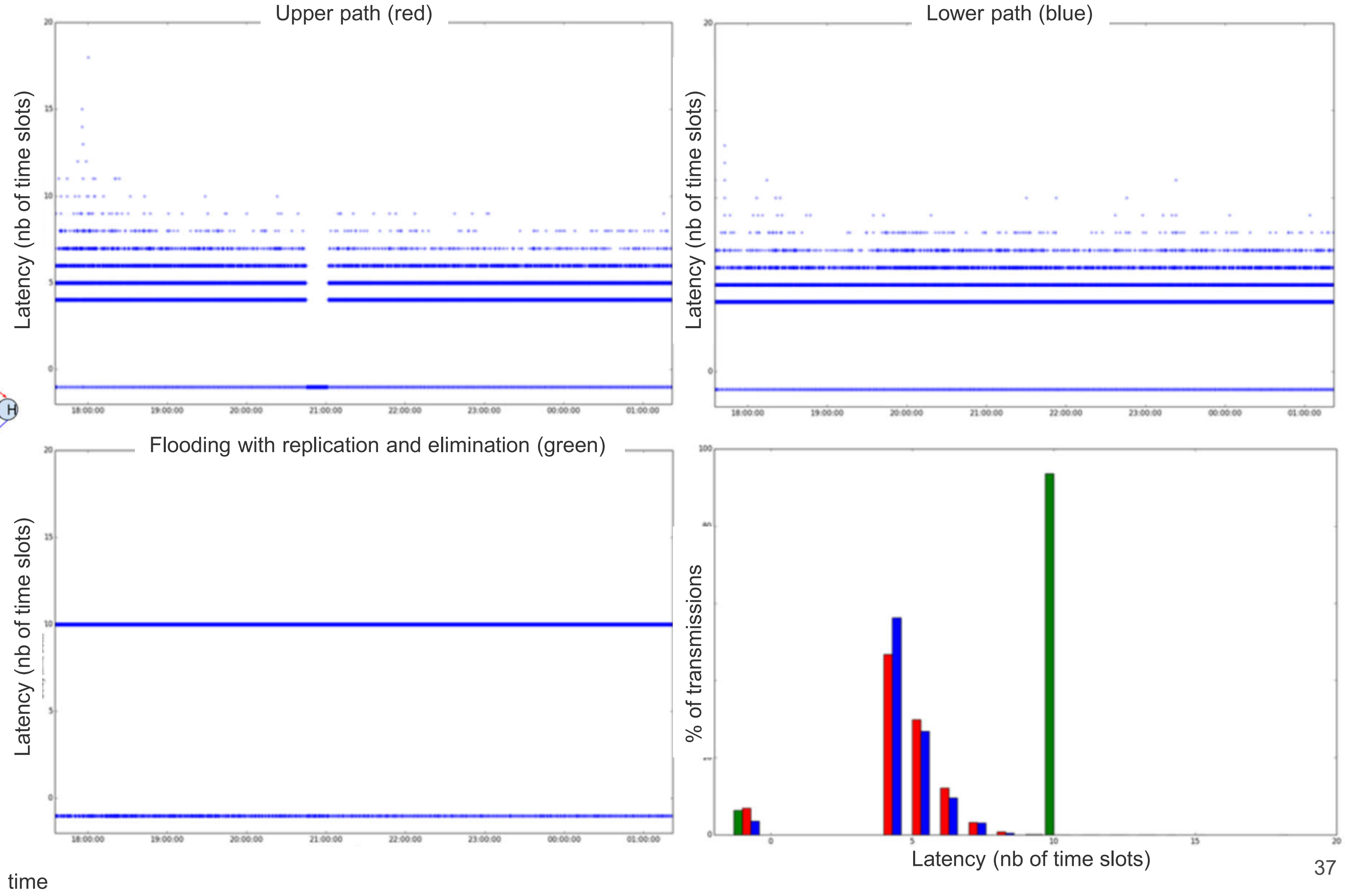
Assigning Time Slot and configuring replication and elimination, each packet with 2 receive opportunities
Time slots taken from a schedule shared with IP/6TiSCH




| timeSlot | Adjacency |
|---|---|
| 0 | I->A |
| 1 | I->B |
| 2 | A->B |
| 3 | B->A |
| 4 | A->C |
| 5 | B->D |
| 6 | C->D |
| 7 | D->C |
| 8 | C->E |
| 9 | D->E |

# Test1: Replication and Elimination vs. Serial Path

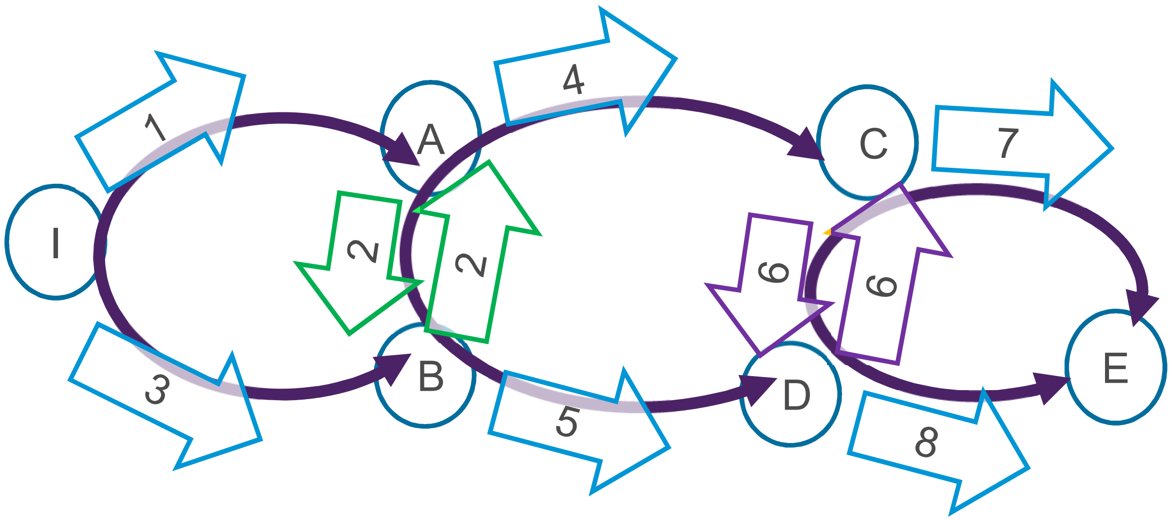


# Test 2 controlling unicast in the ARC chain

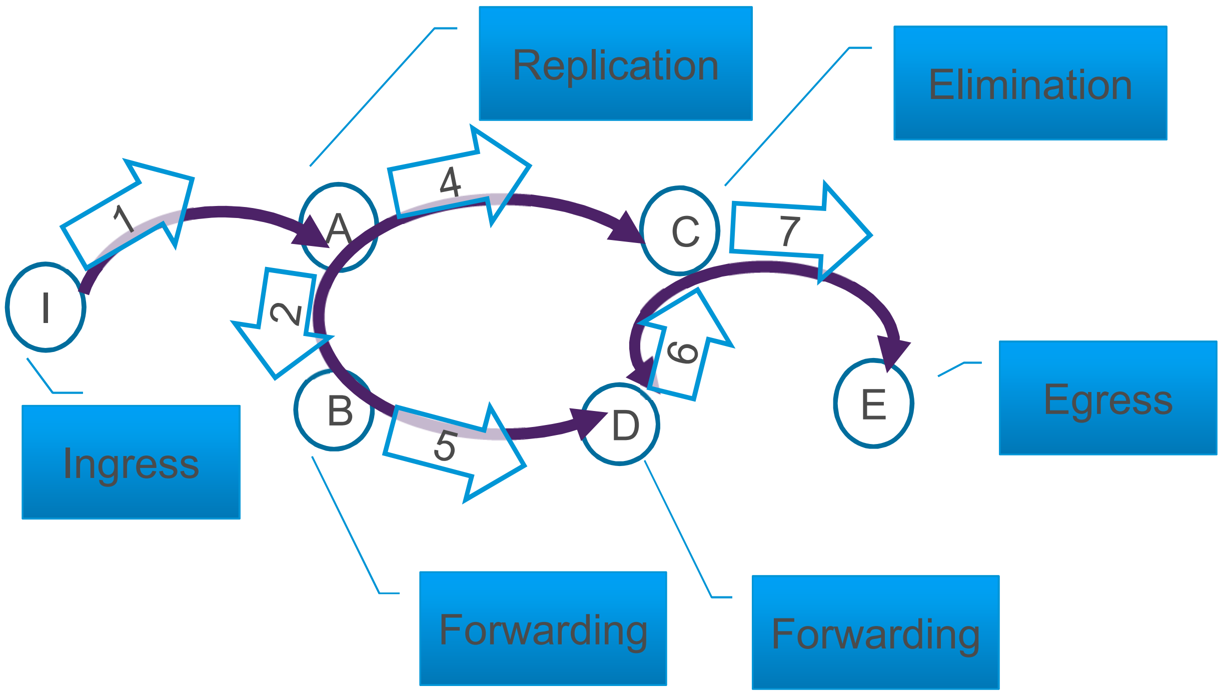
<u>Novelty: dynamic (in band) control of the replication and elimination operation</u>

Segment Activity is controlled in band with packet header
Knowledge of ownership is programmed in the devices



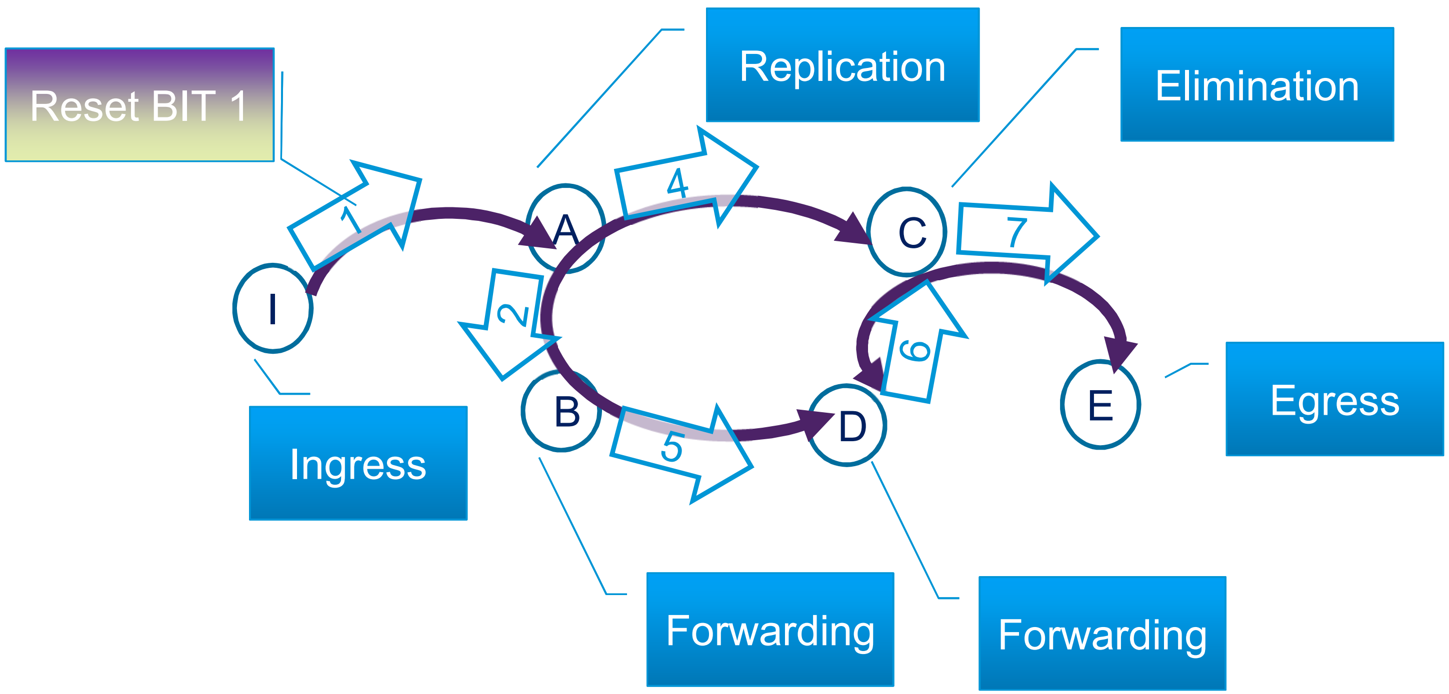

| ctrl# | Adjacency | Owner |
|---|---|---|
| 1 | I->A | I |
| 2 | A->B | A |
| | B->A | B |
| 3 | I->B | I |
| 4 | A->C | A |
| 5 | B->D | B |
| 6 | C->D | C |
| | D->C | D |
| 7 | C->E | C |
| 8 | D->E | D |

# Replication and Elimination Protecting segment A->C



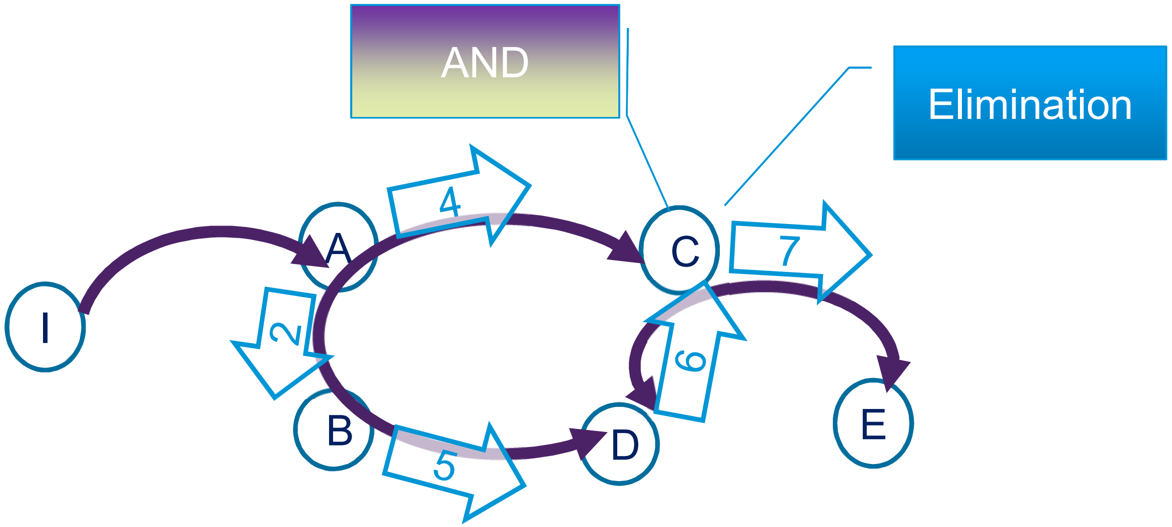

| Bit # | Adjacency | Owner | Example Bit Setting |
|---|---|---|---|
| 1 | I->A | I | 1 |
| 2 | A->B | A | 1 |
| | B->A | B | |
| 3 | I->C | I | 0 |
| 4 | A->C | A | 1 |
| 5 | B->D | B | 1 |
| 6 | C->D | C | 1 |
| | D->C | D | |
| 7 | C->E | C | 1 |
| 8 | D->E | D | 0 |

# Resetting control bits along forwarding segment



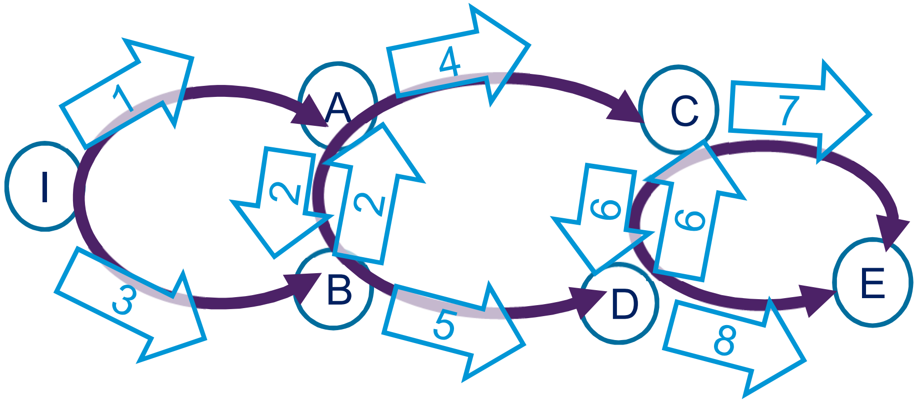

| Adjacency | BIER BitString |
|---|---|
| I->A | 01011110 |
| A->B | 00011110 |
| B->D | 00010110 |
| D->C | 00010010 |
| A->C | 01001110 |

# Elimination nodes AND the bitstrings



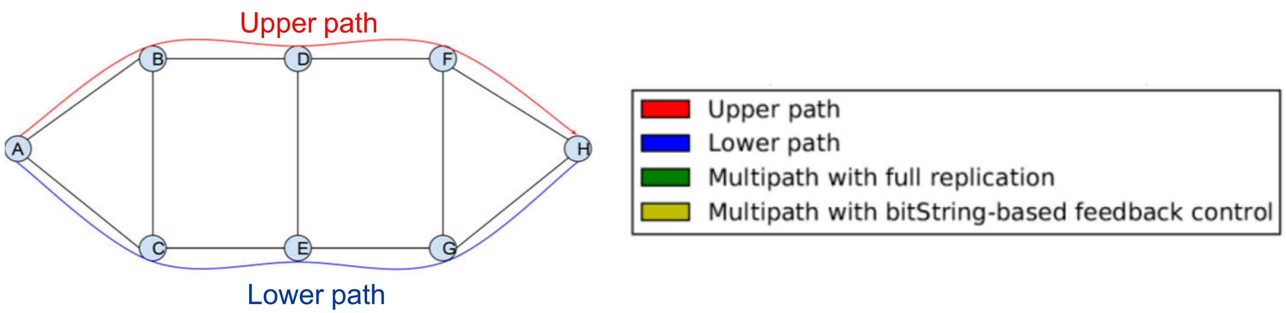

| Operation | BIER BitString |
|---|---|
| **D->C**<br>**A->C** | 00010010<br>01001110 |
| **AND in C** | 00000010 |
| **C->E** | 00000000 |

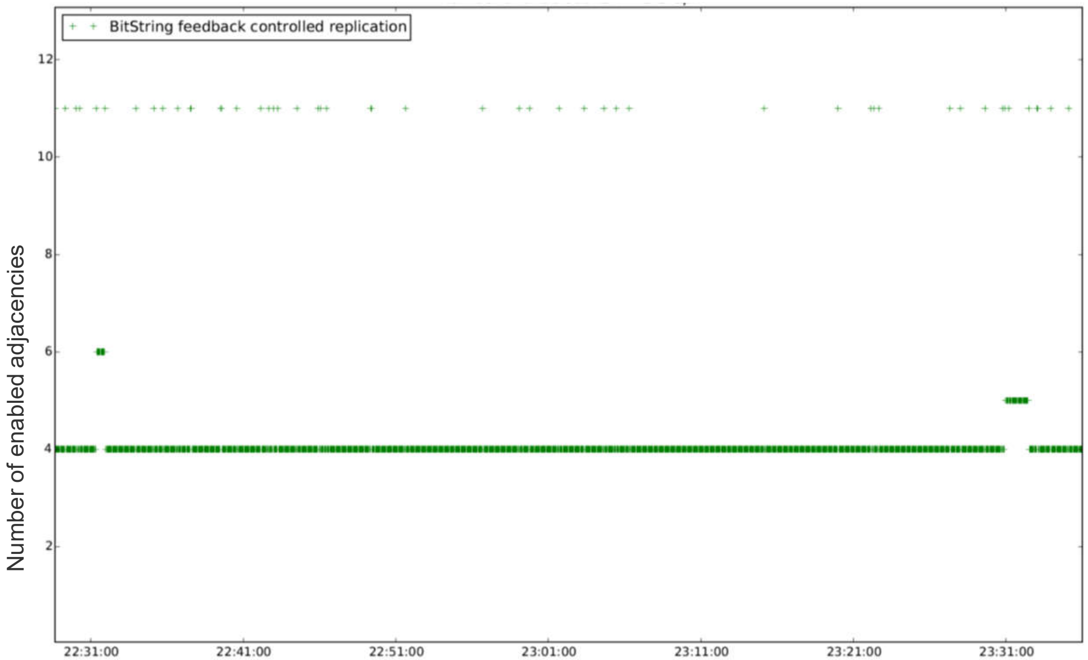
# Detecting and routing around errors

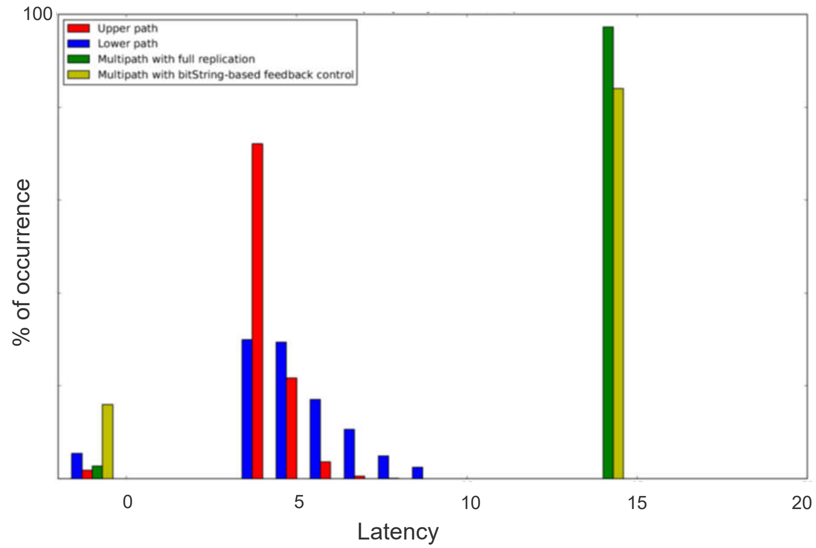


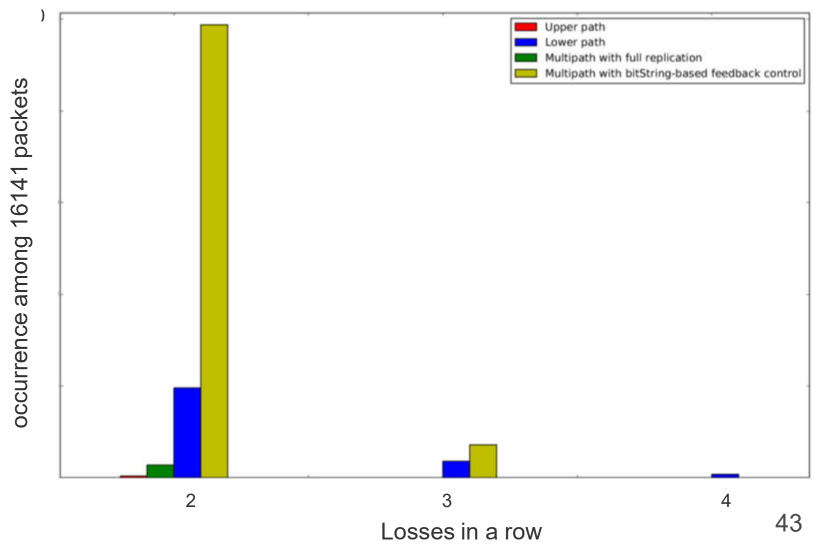

| Failing Adjacency | BIER BitString at Egress |
|---|---|
| I->A | Frame Lost |
| I->B | Not Tried |
| A->C | 00010000 |
| A->B | |
| B->D | 01001100 |
| D->C | |
| C->E | Frame Lost |
| D->E | Not Tried |

# Test 2: Energy Saving

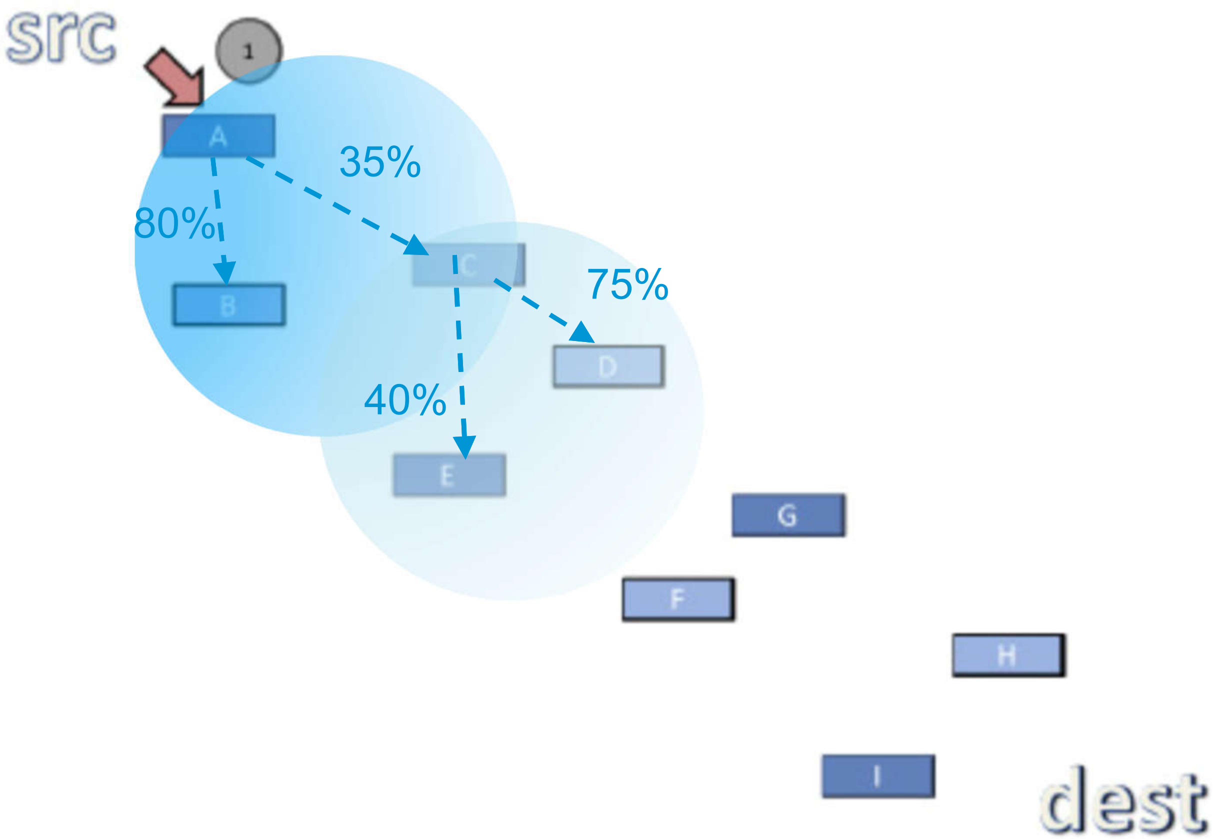


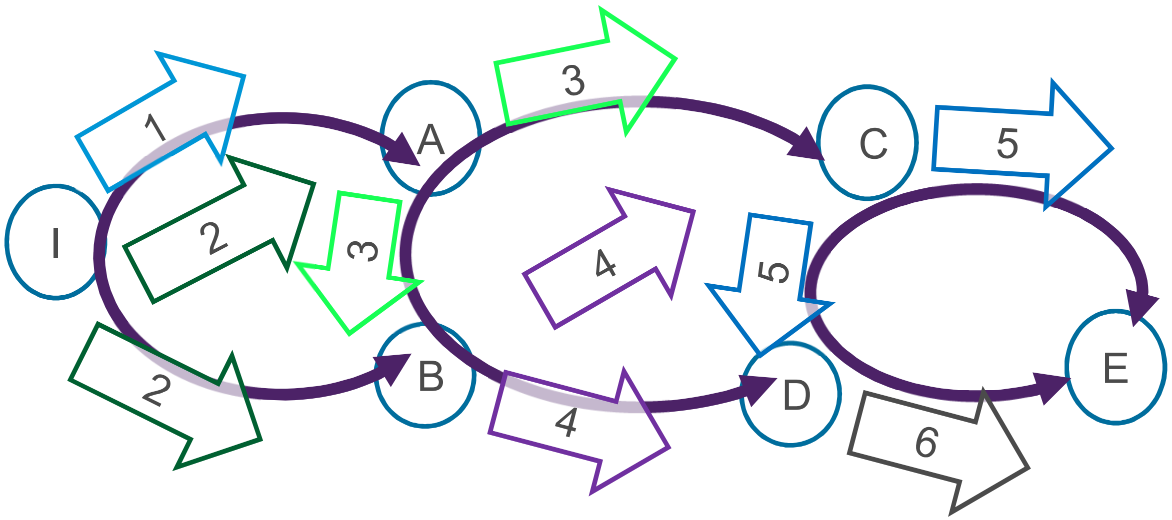
# Test 3: Collaborative Overhearing



# Test 3: Controlling bicasting in the ARC chain

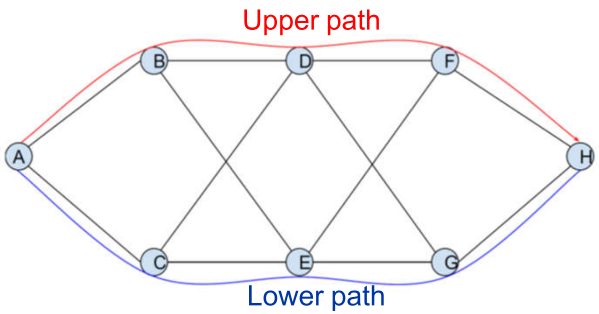
Novelty: Collaborative overhearing to improve latency while preserving energy

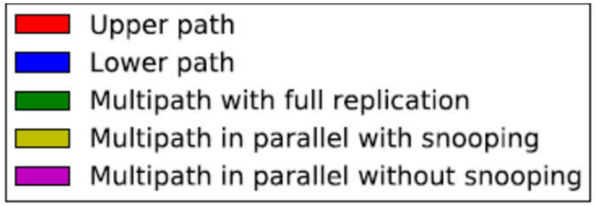
Use RPL non storing mode to expose topology
Enables and schedules >1 downstream listeners

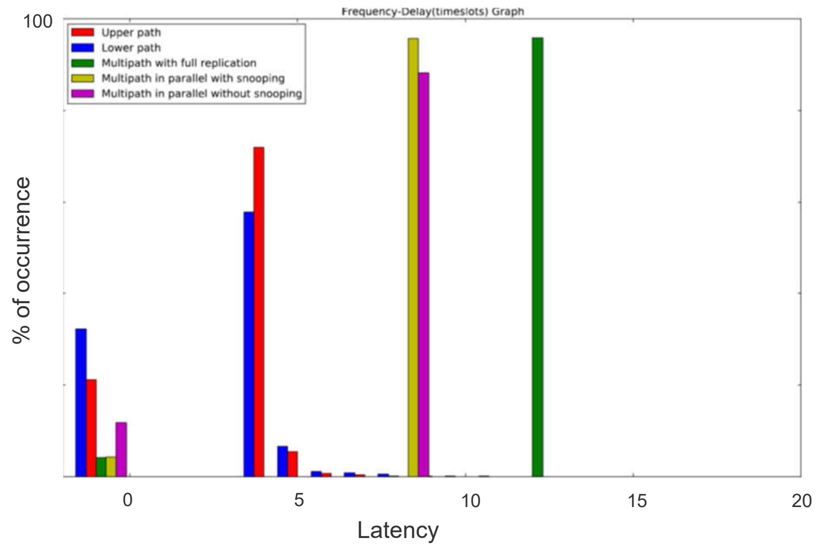



| ctrl # | Adjacency | Owner |
|---|---|---|
| 1 | I->A(,B) | I |
| 2 | I->B,A | I |
| 3 | A->C,B | A |
| 4 | B->D,C | B |
| 5 | C->D,E | C |
| 6 | D->E | B |

# Test 3: Saving Time and Energy with the Leapfrog collaboration



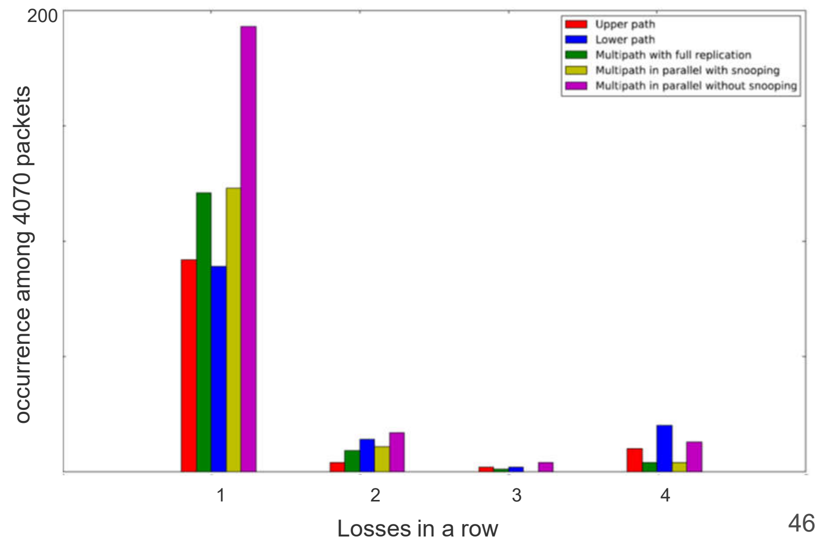




Multipath with full replication:

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A --> B | A --> C | B --> E | B --> D | C --> E | C --> D | D --> G | D --> F | E --> G | E --> F | F --> H | G --> H |

Multipath in parallel with snooping:

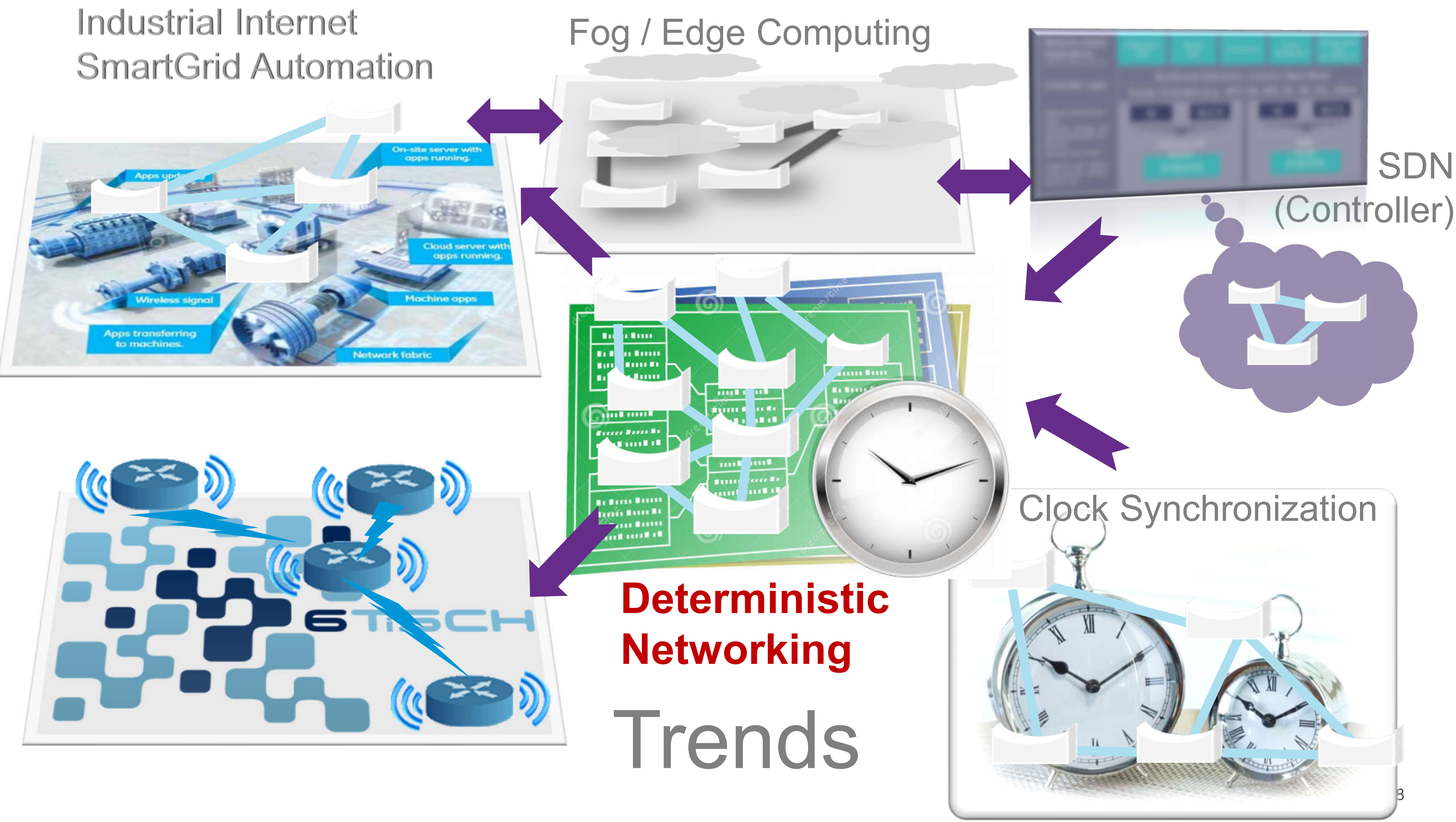
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A --> B,C | A --> C,B | B --> E,D | C --> E,D | D --> G,F | E --> G,F | F --> H | G --> H | | | | |




Multipath in parallel without snooping:

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A --> B | A --> C | B --> D | C --> E | D --> F | E --> G | F --> H | G --> H | | | | |

# In a nutshell


Industrial Internet
SmartGrid Automation
On-site server with apps running.
Cloud server with apps running.
Wireless signal
Machine apps
Apps transferring to machines.
Network fabric
Fog / Edge Computing
SDN
(Controller)
6TiSCH
Deterministic
Networking
Trends
Clock Synchronization

# Take away: The Industrial Internet challenge

Field is after next % point of operational optimization:

Requires collecting and processing of live "big data", **huge amounts of** missing measurements by widely distributed sensing and analytics capabilities.

Often sharing the same medium as critical (deterministic) flows used for Industrial control loops and motion control

Achievable by combination of the best of IT and OT technologies together, forming the IT/OT convergence, aka **Industrial Internet**.

The **next problem** is to extend Deterministic OT traffic to share bandwidth with non-deterministic IT traffic, reaching higher scales at lower costs.

Thank you.