Industrial Internet and the need for guarantees (6TiSCH)

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Agenda

• Industrial IoT
• Performance Requirements of IIoT?
• Time Sensitive / Deterministic Networking
• TSCH
• 6TiSCH
• Conclusion

• Call for memberships – IEEE P 1931.1 WG
Industrial IoT (IIoT)

• Industry 4.0
  • Multiple sectors, application domains
  • Several implementations
  • Estimated market – USD 934 B by 2025
  • IIoT – 55% market share
Industrial IoT (IIoT)

Connected Industry: 22%
Smart City: 20%
Smart Energy: 13%
Connected Car: 13%
Other: 8%
Smart Agriculture: 6%
Connected Building: 5%
Connected Health: 5%
Smart Retail: 4%
Smart Supply Chain: 4%

N = 640 global, publicly announced IoT projects

1. Based on 640+ publicly known enterprise IoT projects, not including consumer IoT projects, e.g., Wearables, Smart Home.
Industrial IoT

• Sensors and actuators deployed before IoT
• Communications systems based on
  • Wireless HART
  • Foundation FIELDBUS
  • Profibus
  • Controller Area Network
• Push for IP-based standardisation (last 3 decades)
• Stringent time and performance requirement
  • Time-constrained communications (bounded e-to-e delays)
• Other requirements
  • Bounded latency, high reliability, energy efficiency
Industrial IoT

- Sensors and actuators deployed before IoT
- Communications systems based on:
  - Wireless HART
  - Foundation FIELDBUS
  - Profibus
  - CAN
- Push for IP-based standardisation (last 3 decades)
- Stringent time and performance requirements
  - Time-constrained communications (bounded to delays)
- Other requirements
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Industrial IoT

- Closed loop industrial automation
  - Front-ends are wireless sensor-actuator networks
  - Back-ends are clouds at the edge and the core
- Real time operation, with latency bounds
- Technology support
  - Deterministic Networking (DetNet)
  - Focus on flow efficiency (resource efficiency in the Internet)
  - What are the differences?
- Dependable control
  - Real time (back-ends real time?)
  - Resilience
  - Control performance

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Constant Bit Rate</th>
<th>Best-Effort</th>
<th>Deterministic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connections?</td>
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<td>Allocated resources along fixed paths</td>
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<td>End-to-end latency</td>
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<td>Primary causes of packet loss</td>
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# Industrial IoT

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Packet Loss and Latencies

Best-effort

C B R

Deterministic
DetNet Features

• Time sync’ed nodes – IEEE 1588 PTP - required by most DetNet applications

• Contracts between transmitters and the network to govern individual flows
  • Flexible contracts
  • No congestion loss, bounded latency
  • Very reliable packet delivery
  • Co-existence with best-effort services (single infrastructure)

• Requires tight control of physical operations and scheduling of real buffers and queues, receiving, shaping and resending packets at precise times
Layer 2

• DetNet operation at Layer 3 will require services from lower layers to achieve the required properties end-to-end
  • IEEE Std 802.1TM for the Professional Media Networks (First generation Ethernet-based standards, called Audio/Video Bridging (AVB)).
  • With Time Slotted Channel Hopping (TSCH), IEEE Std 802.15.4 evolved into a highly predictable, quasi-deterministic Medium Access Control (MAC) technology.
    • Wireless HART (HART 7), ISA100 use TSCH
  • The Time-Sensitive Networking (TSN) Task Group (TG) at the IEEE and the Deterministic Networking (DetNet) Working Group (WG) at the IETF are now generalizing those methods to transport deterministic flows across Ethernet bridges and over IP networks, respectively.
What we want – Wireless Detnets

• Radio and channel related issues impact determinism

• Channel
  • Congested ISM band
  • Varying channel conditions
  • Fixed channels not feasible – Channel agility

• Radio
  • Co-channel interference and multi-path fading
  • Channel access – contention delays, back-offs

• Time Slotted Channel Hopping (TSCH)
  • Schedule transmissions
  • Time and frequency diversities
What we want – Wireless Detnets

- Radio and channel related issues

<table>
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<tr>
<th>Protocol</th>
<th>Year</th>
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<td>CoAP</td>
<td>2014</td>
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<td>RPL</td>
<td>2012</td>
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<td>6LoWPAN</td>
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IP Connectivity
- Web-like services
- Ease of use

IEEE
- Industrial Deployments
  - Performance
  - Reliability
  - Low maintenance

802.15.4
- Time Slotted Channel Hopping (TSCH) - 2012
IEEE 802.15.4

• Standard for low-rate, low-power, and low-cost Personal Area Networks (PANs)
• Network topologies are star (single-hop), cluster-tree and mesh (multi-hop)
• A beacon enabled (BE) mode and a non-beacon enabled (NBE) mode
• The active period is denoted as Superframe Duration (SD) divided into a Contention Access Period (CAP) and a Contention Free Period (CFP)
• CAP = slotted CSMA/CA for channel access, CFP = TDMA using a number of Guaranteed Time Slots (GTSs), pre-assigned to individual nodes
Limitations of IEEE 802.15.4

• **Unbounded Delay.** CSMA/CA cannot provide any bound on the maximum delay

• **Limited communication reliability.** BE mode has very low PDR; NBE mode when a large number of nodes start transmitting simultaneously (e.g., in event-driven applications)

• **No protection against interferences/fading**

• **Energy Consumption** Relay nodes in a multi-hop topology require to keep their radio ON, always
IEEE 802.15.4e TSCH

• Time Slotted (TSCH)
  • Time is divided in slots
  • All motes are *synchronized* to a given *slotframe* (group of slots which repeats over time)
  • Number of slots in a slotframe is configurable

• Channel Hopping (TSCH)
  • 16 channels, 2.4GHz band
  • Each slot used by any node = *Increased Network capacity*
  • The channel offset is translated into a frequency (i.e., a real channel)
  • Nodes use different channels for each packet = *minimise Interference and multipath fading*
IEEE 802.15.4e TSCH

• Scheduling transmissions
  • Each node follows a schedule (a cell matrix)
  • Each cell in the schedule is assigned to a pair for one-way communication
  • A schedule is built either centrally or distributed with application requirements (latency, bandwidth, energy consumption, etc.)
  • A cell can be both dedicated or shared (TSCH-CSMA/CA)
Channel Distribution/Usage

• Switching
  • frame can be switched based on the particular time and the particular channel at which it was received

• Channel Distribution/Usage Matrix (CDU)
  • Global to network
  • *Cells*, each of a certain *timeslot*

```
<table>
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<tr>
<th>slotOffset, 0 .. N</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-15ms</td>
</tr>
<tr>
<td>channelOffset – Max 16</td>
</tr>
</tbody>
</table>
```

Cell (slotOffset, channelOffset)
Slotframe
CDU

• A Chunk is a list of cells with similar properties, well distributed in time and frequency.
• A node gets the ownership of a chunk and decides which transmissions will occur over the cells in the chunk.
• Application flows from a single node can be scheduled on different frames with different priorities, to support concurrent operations (Rx, Tx).
• Bundle – group of cells scheduled for the same purpose. Represents a half-duplex link with a bandwidth of the total cells in the bundle.
Tracks & Links

[Diagram showing network connections and data flows]
IEEE 802.15.4e TSCH

- Schedule: based on specific application requirements - latency, bandwidth, energy consumption, etc.
- Approaches to build a schedule
  - **Centralized**
    - PCE responsible for building and maintaining the schedule
    - Efficient for static networks
  - **Distributed** (MPLS-like)
    - Nodes decide locally which cells they will use for communicating with their neighbors
    - Suitable for mobile networks with many gateways
Centralised Scheduling

1. Nodes send periodic information to Path Computation Element (PCE)
   - Connectivity
   - Traffic requirements
2. PCE computes the TSCH schedule
3. PCE communicates with nodes to configure the schedule (CoAP)
Distributed Scheduling

• A sends a packet along the A→B→D→E multi-hop path (circuit?)
• At each hop, neighbor motes negotiate with one another to add cells into their TSCH schedule (bandwidth)
• 6top monitoring process recovers from topological changes and collisions by rescheduling badly performing cells
• Nodes have the same maximum number of possible channel access attempts $maxA$ in both protocols

• TSCH provider higher reliability as well as a higher latency(!)
What we want – Wireless Detnets

- Radio and channel related issues

- Radio and channel related issues
  - Radio and channel related issues
  - Radio and channel related issues

  CoAP (2014)

  RPL (2012)

  6LoWPAN (2011)

- IP Connectivity
  - Web-like services
  - Ease of use

- 802.15.4
  - Time Slotted Channel Hopping (TSCH) - 2012

- Industrial Deployments
  - Performance
  - Reliability
  - Low maintenance
Stacking the layers

- Time-sensitive IPv6 traffic (OT traffic)
- Use 802.15.4 deterministic mode with TSCH
- IETF 6TiSCH WG – 2013
The 6TiSCH Operation sublayer (6top) is a sublayer of a Logical Link Control (LLC) that provides the abstraction of an IP link over a TSCH MAC and schedules packets over TSCH cells.
Summary

• Both wired and wireless networks are evolving towards more determinism needed by IIoT
• Operational Technologies (OT) require a specific performance, vastly different from traditional IT
• OT and IT have to converge on a shared network; Current OT networks are separate networks
• 6TiSCH provides a means to evolve towards this convergence
  • Deterministic and best-effort traffic
  • Best average delivery time and lowest energy consumption
On-going work in the IETF

• 6top Protocol (6P) -
draft-ietf-6tisch-6top-protocol-09
  • 6P is part of the 6top sub-layer, the layer above the IEEE Std 802.15.4 TSCH MAC layer. A 6top Scheduling Function (SF) decides when to add/delete cells, and triggers 6P Transactions.

• 6TiSCH 6top Scheduling Function Zero - draft-ietf-6tisch-6top-sfx-00
  • "Scheduling Function Zero" (SF0) dynamically adapts the number of scheduled cells between neighbor nodes, based on the amount of currently allocated cells and the neighbor nodes' cell requirements. SF0 uses the 6P signaling messages to add/delete cells in the schedule.

• An Architecture for IPv6 over the TSCH mode of IEEE 802.15.4 - draft-ietf-6tisch-architecture-12
  • Network architecture that provides low-latency, low-jitter and high-reliability packet delivery.

• Terminology in IPv6 over the TSCH mode of IEEE 802.15.4e draft-ietf-6tisch-terminology-09
On-going work at the IETF

- Minimal Security Framework for 6TiSCH
draft-ietf-6tisch-minimal-security-03
  - The minimal mechanisms required to support secure enrollment of a pledge, a device being added to a 6TiSCH network. The goal of this configuration is to set link-layer keys, and to establish a secure end-to-end session between each pledge and the join registrar who may use that to further configure the pledge

- 6tisch Zero-Touch Secure Join protocol
draft-ietf-6tisch-dtsecurity-zerotouch-join-00
  - A zero-touch mechanism to enroll a new device (the "pledge") into a IEEE802.15.4 TSCH network using the 6tisch signaling mechanisms.
References

• Hsieh, C. Energy Efficiency and Reliability on Wireless Sensor Actuator Network, KIT, Germany

• www.iot-analytics.com

• Lu, C. Real-time Internet of Things. Cyber-Physical systems laboratory, Washington University

• Finn, N. 2017. Time-sensitive and Deterministic Networking. Huawei Technologies Co. Ltd.


• ETSI 2017. IPv6-based Industrial Internet leveraging 6TiSCH technology. Group Report - ETSI GR IP6 009 V1.1.1 (2017-03)
Roof Computing

- Real-time On-site Operations Facilitation (ROOF)

Establishing peer-to-peer trust
Sharing & collaboration
Establishing reputation
Roof vs. Fog vs. Cloud

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Computing Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Roof</td>
</tr>
<tr>
<td>Distance to Things</td>
<td>Few meters</td>
</tr>
<tr>
<td>Deployment numbers</td>
<td>Millions to billions</td>
</tr>
<tr>
<td>Technology complexity</td>
<td>Simple</td>
</tr>
<tr>
<td>Implementation complexity</td>
<td>Easy</td>
</tr>
<tr>
<td>Content</td>
<td>Machine data</td>
</tr>
<tr>
<td>Drivers</td>
<td>The things - constrained devices</td>
</tr>
<tr>
<td>Applications</td>
<td>Context aware realtime applications</td>
</tr>
<tr>
<td>Cost of implementation</td>
<td>Low</td>
</tr>
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IEEE Standards Development Working Group, ROOF – Roof Computing
https://standards.ieee.org/develop/wg/ROOF.html

Calling for memberships to the WG: Contact

Dr. P. Ambika, ambika.p@kristujayanti.com
Thank you