6TiSCH
towards an IPv6-based Industrial Internet
Technical Track
Why the IT/OT convergence?

Operational technology (OT) is hardware and software that detects or causes a change through the direct monitoring and/or control of physical devices, processes and events in the enterprise.

Next % point of optimization => 100s of billions savings / next 15 years.

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

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

Deterministic Wireless Industrial Networking technologies must be extended to reach higher scales at lower costs (with lower guarantees).

Architectural approach, standards, Industry adoption needed to embrace radical changes happening in IT networking technologies.

Secured-by-default model required throughout network lifecycle.
Industrial connected device growth

Figure 8.8
Industrial - Internet Connected Devices - New Shipments by Connectivity and Class

000s of Connected Devices

- WWAN
- WLAN
- WPAN
- Wired

Source: IMS Research

Aug-12

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

**IEEE**

Covers MAC and eventually LLC
Also link security (CCM*, 802.1x)

**IETF**

Typically routing, end-to-end security and transport
RPL, DTLS, CoAP
Trouble: 7000+ RFCs
Trouble: problem spanning layers and SDOs

**Industry alliances for test and certification**

**6TiSCH is an harmonized solution**

IETF + IEEE extensions via IG

The 6TiSCH WG is chartered to provide a bundled architecture based on (mostly) existing RFCs.
IEEE802.15.4e TimeSlotted Channel Hopping (TSCH)

Schedule => direct trade-off between throughput, latency and power consumption. A collision-free communication schedule is typical in industrial applications. IEEE802.15.4e published April 2012.

15.4e defines how to execute a schedule, but not how to build/maintain it.
Case for IPv6 addressability

OnWorld conducted polls and published results based on interviews with 105 plant managers, process integrators and system engineers.

Results are clearly indicative of industrial end user’s concerns.

IPv6 addressability is a major factor for adoption of wireless technologies employed in industrial automation.

IPv6 addressability is tightly coupled with future extensibility of industrial wireless standards based products.

Adoption Factors
(Combined Total for Ranking Score of 1-5, 5= Most Likely)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long battery life</td>
<td>77.4%</td>
</tr>
<tr>
<td>Low cost</td>
<td>74.1%</td>
</tr>
<tr>
<td>IP addressability</td>
<td>65.6%</td>
</tr>
<tr>
<td>Single plant network</td>
<td>65.6%</td>
</tr>
<tr>
<td>Standards</td>
<td>82.0%</td>
</tr>
<tr>
<td>Ease of use</td>
<td>81.4%</td>
</tr>
<tr>
<td>Data reliability</td>
<td>95.5%</td>
</tr>
<tr>
<td>Security</td>
<td>80.3%</td>
</tr>
</tbody>
</table>
6TiSCH: IPv6 over TSCH

Large scale IPv6 subnet with backbone (50K +)
Integrated autonomic bootstrap & security profiles
Designed for time-sensitive IEEE802.15.4e TSCH
Direct IPv6 access to device
e.g. for common network management

Integrates RPL (RFC 6550)
Distributed Routing Protocol designed by IETF
Coming with distributed scheduling
Supports loopless time distribution
Addressing Industrial applications and needs

Control Loops
require tight latency control
Fully scheduled operations
Centralized routing computation
Short periods (order of a second)

Large Scale Monitoring (10Ks and more)
e.g. Corrosion: Long lines along pipes, widespread over tanks
Required distributed operations for scheduling and routing
Live “Big Data” is an Emerging application, not fully covered by existing standards
Longer periods (order of a day)
Highly sensitive to power consumption
Centralized vs. Distributed routing

**Centralized**
- God’s view optimization
- Multipath redundancy
- Deterministic (optimized)
- Virtualization

**Distributed**
- Autonomic & Mobile
- Highly available (DARPA)
- Deterministic
- Scalability
Example radio connectivity

At a given point of time connectivity is (fuzzy)
Applying RPL

1st pass (DIO)
Establishes a logical Directed Acyclic Graph (DAG) topology
Trickle Subnet/config Info
Sets default route
Self forming / self healing

2nd pass (DAO)
paints with addresses and prefixes
Any to any reachability
But forwarding over DAG only saturates upper links of the DAG
And does not use the full mesh properly
Local recovery (step 1)

A’s link to root fails
A loses connectivity
Either poisons or detaches a subdag

In black:
the potentially impacted zone
That is A’s subDAG
Local recovery (step 2)

B can re-parent a same Rank so B’s subDAG is safe

The rest of A’s subDAG is isolated

Either poison ar build a floating DAG as illustrated
In the floating DAG A is root
The structure is preserved
Once poisoned nodes are identified
It is possible for A to reparent safely
A’s descendants inherit from Rank shift
Note: a depth dependent timer can help order things
A new DAG iteration

- In black, the new DAG progressing

Metrics have changed, the DAG may be different

Forwarding upwards traffic from old to new iteration is allowed but not the other way around
Multiple DODAGs within Instance

A second root is available (within the same instance)

The DAG is partitioned
1 root = 1 DODAG
1 Node belongs to 1 DODAG (at most, per instance)

Nodes may JUMP from one DODAG to the next

Nodes may MOVE up the DODAG

Going Down MAY cause loops
May be done under CTI control
Multiple Instances

Running as Ships-in-the-night
1 instance = 1 DAG
A DAG implements constraints
Serving different Objective Functions
For different optimizations
Forwarding along a DODAG (like a vlan)
Current architecture: isolated networks

Limit of IP direct connectivity

Control loop limited to subnet
No end-to-end IP connectivity
No single view management
No IP in control loop
6TiSCH subnets connected to carpeted floor
IT/OT Network Convergence

Converged Plant Network
- High availability
- Flow Isolation
- Guaranteed Bandwidth

IP based Control Network
- Autonomic, zero touch commissioning
- Time Sensitive Networking for critical apps
- Packet Reliability

IPv6-based Wireless Field Network
- Deterministic, Autonomic, Secure
- Large Scale for Monitoring (RPL)
- Backward Equivalence (TSCH)
Thank You
The Case for Industrial Wireless

Cables can be inappropriate
- for rotating devices, moving cranes, robots arms or mobile handheld devices

Cables are expensive
- Wire buried in conduit has high installation and maintenance cost, long lead time and extreme difficulties to repair

GE’s 1% lead to $15M/year in just 1 refinery
- Better process optimization and more accurate predictive maintenance increase profit
- Thus more and different sensors can be justified economically, if they can be connected
Random Access vs. scheduled MAC operations

Classical Random Access IEEE 802.15.4 (Zigbee IP, Zigbee)
- Long preamble; medium sampling
- 16 channels in the 2.4GHz ISM band,
- Similar to WiFi but simpler and less aggressive
- Simple / Ideal for stochastic traffic

Wi-SUN
- Adds Frequency Agility to defeat interferences and multipath

Scheduled IEEE 802.15.4e TimeSlotted Channel Hopping (TSCH)
- On of multiple modes in the new open standard
- Optimal battery consumption for deterministic sources (traffic known a priori)
- Enables Time Sensitive applications (ISA100.11a, WirelessHART)
- New IEEE Interest Group to support IETF work over this MAC (6TiSCH)
Wireless Sensors Networks in Industrial Applications

WSNs can be used advantageously for rare event detection or periodic data collection for industrial applications. In rare event detection, sensors are used to detect and classify rare, random, and ephemeral events, such as alarm and fault detection notifications due to important changes in machine, process, plant security, operator actions, or instruments that are used intermittently.

On the other hand, periodic data collection is required for operations such as tracking of the material flows, health monitoring of equipment/process. Such monitoring and control applications reduce the labour cost, human errors and prevent costly manufacturing downtime.

What people usually miss is the order of magnitude. For each ‘critical’ wired measurement (e.g. control loops) there are hundreds missing ones that could (only) be addressed through wireless. Aiming at a scale a thousand times larger than early WSN deployments.

Missing measurements are the key to GE’s 1% that justifies the Industrial Internet.

http://community.emerson.com/process/emerson-exchange/b/weblog/archive/2013/10/03/why-are-there-missing-measurements.aspx
Best effort routing

A

1TX

B

1+1TX

CoAP

UDP

IPv6

6LoWPAN-HC

6top

15.4e TSCH

15.4 PHY

C

Y

1RX

X

1TX

6top

6top

15.4 PHY

15.4 PHY

D

U

Bundle

channel/offset

A → X

B → X

X → Y

Y → V

X → Y

Y → U

A → Y

B → X

2014 Industry Conference & 16th Annual Meeting

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Track Switching in Transport Mode

A

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

X

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4 PHY

Y

X → Y
Y → U

2TX
2RX

1RX

1TX

A

X

Y

B

V

U

Track

channelOffset

slotOffset
Track Switching in Tunnel Mode

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4e TSCH
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4e TSCH
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4e TSCH
15.4 PHY

CoAP
UDP
IPv6
6LoWPAN-HC
6top
15.4e TSCH
15.4 PHY

15.4 PHY
TSCH
Multi-
6LoWPAN Fragment forwarding

- CoAP
- UDP
- IPv6
- 6LoWPAN-HC
- 6top
- 15.4 TSCH
- 15.4 PHY

Diagram shows the flow of data through various protocols and components, including
- CoAP
- UDP
- IPv6
- 6LoWPAN-HC
- 6top
- 15.4 TSCH
- 15.4 PHY

The diagram illustrates the path from A to U, involving intermediate nodes and channels.

Bundle:

- X → Y
- Y → V

Channel Offset:

- A → X
- X → Y
- Y → U
- B → X

Slot Offset:

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Benefits

For Users

- A step toward Harmonization (Hour Glass model)
- COTS price, Standard experience (e.g. crypto),
- IPv6 end to end, enabling virtualization, thus easier install and management
- Deterministic to the carpeted floor, enabling control loops with virtual PLC

For Vendors

- Extends value proposition, less dedicated hardware, more software
- Extends the reach of IP technology, save on generic soft and hard components
- Reusable Improvements on generic capabilities (e.g. deterministic switching)
- App Servers in the control loop, added value in fog/cloud analytics
Scalability requirements

10s of Ks devices with multihop LLN access
- No broadcast in the LLNs
- No renumbering (quasi permanent IPv6 address)

Continuous reachability as a LLN device moves in Subnet
- Radio conditions change cause network reorganisation
- Already use cases such as handheld, cranes, small vehicles

Backward Compatibility with classical IPv4 and v6 devices

Support of discovery protocols throughout the subnet
Routing requirements

Cost Optimized in the backbone
» Any to any traffic
» Multipath and load balancing a bonus

Power Optimized in the LLNs
– Most traffic flows to or from the LLN Backbone Router
– Control traffic must be limited vs. Data traffic

Broadcast or scalable multicast in the backbone
Multicast or Controlled dissemination in the LLN
Time-Sensitive requirements

LLNs Time synchronization via the backbone to keep all LLNs in sync and allow movement from one LLN to the next

Slow deterministic LLNs (proces control)
No need for Deterministic backbone
Until scale and congestion loss becomes an issue

Upcoming faster deterministic wireless (factory automation)
deterministic loops across networks and server OS
Compatibility requirements

End-to-End time-synchronization
- Synchronization via the backbone a plus
- Standard time exchange, adapted precision.
- Sync and schedule with the Deterministic backbone

MTU size a complex issue across networks
- Ideally harmonize MTUs across multilink subnet or
- at least detect discrepancies

Link Local lookups should be emulated
- Proxy operation (per protocol)
- Generalized hash based multicast
IEC 62591
IEC based on HART 7.1.
TDMA
fixed time slots (10ms)
Mesh only
Shipped YE-2008.
Vendor driven
Emerson, E&H, ABB, Siemens

IEC PAS 62734
IEC based on 2011 revision
TDMA+CSMA
Var. time slots
Star, mesh and hybrid topology
IPv6, 6LoWPAN, TCP-friendly
Shipped mid-2010
Mostly user driven
Honeywell, Yokogawa, Invensys

IEC 62601
WIA-PA
Alternate from China
Star, mesh and hybrid topology
Standardization work started in 2006.
# 6TSCH: Architecture

Centralized route and track computation and installation

Management and Setup Discovery Pub/Sub

Authentication for Network Access

Distributed route and track computation and installation

<table>
<thead>
<tr>
<th>PCEP/PCE</th>
<th>CoAP/DTLS</th>
<th>PANA</th>
<th>6LoWPAN ND</th>
<th>RPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP</td>
<td>UDP</td>
<td>ICMP</td>
<td>RSVP</td>
<td></td>
</tr>
<tr>
<td>IPv6</td>
<td>6LoWPAN HC</td>
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</table>

Time Slot scheduling and track G-MPLS forwarding
Routing With RPL

Low Power Lossy Nets

Dynamic Topologies
Peer selection
Constrained Objects
Fuzzy Links
Routing, local Mobility
Global Mobility

Addressed in RPL?

- ✔ Dynamic Topologies
- ✔ Peer selection
- ✔ Constrained Objects
- ✔ Fuzzy Links
- ✔ Routing, local Mobility
- ✗ Global Mobility