Reliable and Available
Low-Power Wireless Mesh Networks

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Low-Power Wireless Mesh Networks
Overview

A typical Mesh (multi-hop) Topology

LPWMN consist of “smart”, uniquely identifiable and typically wirelessly connected objects such as Sensors & Actuators that cooperatively construct a wireless network of things, i.e., IoT.

- **Sensors**: Temperature, Humidity, Pressure, Current.
- **Actuators**: Light, Buzzers, Locks, Valves.
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- **Limited capacity** in terms of memory storage, computational power & energy.
A typical Mesh (multi-hop) Topology

Applications

<table>
<thead>
<tr>
<th>Protocols</th>
<th>IPv6</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoAP / OSCORE</td>
<td>6LoWPAN ND</td>
</tr>
<tr>
<td>6LoWPAN HC / 6LoRH HC</td>
<td>Scheduling Function (MSF)</td>
</tr>
<tr>
<td>UDP</td>
<td>ICMPv6</td>
</tr>
<tr>
<td>IPv6</td>
<td></td>
</tr>
<tr>
<td>6top inc. 6top Protocol (6p)</td>
<td></td>
</tr>
<tr>
<td>IEEE Std 802.15.4 TSCH</td>
<td></td>
</tr>
<tr>
<td>IEEE Std 802.15.4 PHY</td>
<td></td>
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</tbody>
</table>

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## Low-Power Wireless Mesh Networks

### OSI Model vs 6TiSCH Protocol Stack

<table>
<thead>
<tr>
<th>Layer</th>
<th>Protocol data unit (PDU)</th>
<th>Applications</th>
<th>Media layers</th>
<th>IEEE Std 802.15.4 PHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Application</td>
<td>Data</td>
<td>CoJP</td>
<td>6top inc. 6top Protocol (6p)</td>
<td>IEEE Std 802.15.4 TSCH</td>
</tr>
<tr>
<td>6. Presentation</td>
<td>Data</td>
<td>CoAP / OSCORE</td>
<td>Scheduling Function (MSF)</td>
<td>IPv6</td>
</tr>
<tr>
<td>5. Session</td>
<td>Data</td>
<td>6LoWPAN ND</td>
<td></td>
<td>ICMPv6</td>
</tr>
<tr>
<td>4. Transport</td>
<td>Segments, Datagram</td>
<td>RPL</td>
<td></td>
<td>UDP</td>
</tr>
<tr>
<td>2. Data Link</td>
<td>Frames</td>
<td>6LoWPAN ND</td>
<td>Scheduling Function (MSF)</td>
<td>CoJP</td>
</tr>
<tr>
<td>1. Physical</td>
<td>Bits</td>
<td>IPv6</td>
<td>6top inc. 6top Protocol (6p)</td>
<td>CoJP</td>
</tr>
</tbody>
</table>

**Throughput:**
- Gbit/s (Network layer)
- 100 Kbit/s (Physical layer)

**MTU:**
- ~1000 Bytes (Network layer)
- ~100 Bytes (Physical layer)
Toward Reliable & Available Low-Power (Wireless) Mesh Networks
The goal of the reserved bus lanes in a city (for the buses) is to avoid delays due to traffic jams!
The information should be carried out in a pre-defined and constant delay!
Toward Reliable & Available LPWMNs
The Challenge in QoS-hungry networks

The information should be carried out in a pre-defined and constant delay! Thus, in addition to high reliability is to provide a bounded latency.
Toward Reliable & Available LPWMNs
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There's no such thing as a Free Lunch!
- Throughput (network capacity)
- Energy consumption
Toward Reliable & Available LPWMNs
The Challenge in QoS-hungry networks

The information should be carried out **in a pre-defined and constant delay!** Thus, in addition to high reliability is to provide a **bounded latency**.

There’s no such thing as a Free Lunch!
- Throughput (network capacity)
- Energy consumption

Good news!
- Devices are plugged into a power supply.
- Low traffic rate applications.
Toward Reliable & Available LPWMNs
Scientific Approach

- HDR subject!
  - 1 Postdoc
  - 4 PhD students
  - Several Interns

Radio Channel Blacklisting Algorithms
Scheduling Functions
Multipath Routing Strategies

Frequency
Temporal
Spatial

Spatial
Destination

Frequency

Temporal

Unicast TX
Unicast RX
Overhearing RX

Dest.
Int. B
Int. A
Src.

Replication: Src to Int. A & B

OH: Int. B on Src → Int. A

ARQ: Int. B

2MHz 5MHz

2405 2410 2415 2420 2425 2430 2435 2440 2445 2450 2455 2460 2465 2470 2475 2480 (MHz)
Research Methodology Approach
Research Methodology Approach

► Academic Research:
  - Analysis.
  - Simulations (6TiSCH simulator, Cooja, Grid5000).
  - Experiments (Contiki OS, OpenMotes, FIT IoT-LAB).

► Standardization:
  - ROLL, RAW, DetNet, and 6TiSCH WGs.

► Testbeds:
  - OS Electric Vehicle.
  - Renault Fluence Battery Pack.
  - EVs.

► Real-world applications:
  - Wireless BMS with industrial partners (TI and Renault).
Research Methodology Approach
Toward Wireless Battery Management System (BMS)

@IMT Atlantique
Project: Contrat de Recherche Industriel (Texas Instruments)

@IMT Mines Alès
Project: InterCarnot M.I.N.E.S - TSN

@Technocentre Renault
Project: CIFRE (Renault)

From the desk to the car
The employed Protocol Stack
The 6TiSCH Protocol Stack

Overview

- **IPv6**
- **IEEE Std 802.15.4 PHY**
- **IEEE Std 802.15.4 TSCH**
- **CoAP / OSCORE**
- **UDP**
- **IPv6**
- **6LoWPAN HC / Fragment.**
- **Scheduling Function (MSF)**
- **6top inc. 6top Protocol (6p)**
- **CoJP**
- **6LoWPAN ND**
- **RPL**
- **ICMPv6**

**Applications**
- CoJP

**Routing**
- RPL

**Resource Allocation**
- 6P and MSF

**Fragment Forwarding**
- 6LoWPAN

**Medium Access Control**
- TSCH
### The 6TiSCH Protocol Stack

#### Overview

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- **Routing**: RPL
- **Resource Allocation**: 6P and MSF
- **Medium Access Control**: TSCH
RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks
Beyond the radio coverage of one node, it will require a routing protocol.
The 6TiSCH Protocol Stack
RFC 6550: RPL

► One of the most adopted routing protocols.
► Link-layer agnostic.
► Proactive routing protocol.
The 6TiSCH Protocol Stack
RFC 6550: RPL

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- Destination Oriented Directed Acyclic Graph (DODAG):
  - Distance-vector technique.
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- DODAG Root:
  - Serves as gateway to other non-RPL networks.
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Objective Function:
- Each node selects one or more parent(s).

Rank:
- Defines the node's individual position with respect to DODAG root.

The 6TiSCH Protocol Stack
RFC 6550: RPL

DODAG Root

Starts with a default rank e.g., 256

R

D

G

H

I

768

1280

E

F

RFC 6550: RPL

The 6TiSCH Protocol Stack

DODAG Root

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The 6TiSCH Protocol Stack
RFC 6550: RPL

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![Diagram of 6TiSCH Protocol Stack]

Wi-SUN Protocol Stack

Starts with a default rank e.g., 256
Problem Formulation: Routing Layer
Problem Formulation

An example of a crashed node or bad link quality
Problem Formulation

An example of a crashed node or bad link quality

Preferred Parent (PP)

Default RPL operation
Problem Formulation
An example of a crashed node or bad link quality

- Crashed node or heavily interfered radio link:
  - Node failure
  - or poor radio link
Problem Formulation
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  - TSCH: Retransmissions over different radio channels.
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- Crashed node or heavily interfered radio link:
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  - RPL: Local (to select alternative parent) or Global Repair.
Problem Formulation
An example of a crashed node or bad link quality

► Crashed node or heavily interfered radio link:
  - TSCH: Retransmissions over different radio channels.
  - RPL: Local (to select alternative parent) or Global Repair.

► Costs:
  - Latency and jitter increase.
  - End-to-end network reliability decreases.
  - Network (unnecessarily) overloads:
    e.g., the Trickle timer will be triggered.
Separation of PSE from PCE

“IETF Reliable and Available Wireless (RAW): Use Cases and Problem Statement”,
G. Z. Papadopoulos, F. Theoleyre, P. Thubert and N. Montavont,
Path Computation Element (Controller):
- Focus on computing the *routing paths* for the whole network.
Ongoing Work & Perspectives
Separation of PSE from PCE

► Path Computation Element (Controller):
  - Focus on computing the *routing paths* for the whole network.

► Path Selection Engine (PSE):
  - Focus on *forwarding plane* to make the per-packet decision.
  - Employ either commonly or separately the PAREO Functions!
Ongoing Work & Perspectives
Separation of PSE from PCE

Path Computation Element (Controller):
- Focus on computing the *routing paths* for the whole network.

Path Selection Engine (PSE) [3]:
- Focus on *forwarding plane* to make the per-packet decision.
- Employ either commonly or separately the PAREO Functions!

Objective is to separate:
- The *long-term* path computation time scale at which the *paths are recomputed*.
- From the *short-term* path selection time scale at which the *forwarding decision is taken*.
Step 1: PSE - Forwarding Plane
(Meet the PAREO Functions)

“Meet the PAREO Functions: Towards Reliable and Available Wireless Networks”
In Proc. IEEE ICC 2020 - Dublin, Ireland, June 2020
PAREO Functions

- Pool of functions:
  - Packet Transmission
  - Automatic Repeat reQuest (ARQ)
  - Replication
  - Overhearing
  - Elimination
PAREO Functions

- Pool of functions:
  - Packet Transmission
  - Automatic Repeat reQuest (ARQ)
  - Replication
  - Overhearing
  - Elimination

- and more such as:
  - Forward Error Correction (FEC) [1], [2]
  - Packet (Re)Ordering (work-in-progress)


PAREO Functions

► Pool of functions:
- Packet Transmission
- Automatic Repeat reQuest (ARQ)
- Replication
- Overhearing
- Elimination

► and more such as:
- Forward Error Correction (FEC)
- Packet (Re)Ordering
- Constructive Interference


PAREO Functions

Example of a Wireless Topology

- S is the Source
- R is the Root (destination)
- Relay nodes

\[ S \rightarrow M \rightarrow N \rightarrow O \rightarrow P \rightarrow Q \rightarrow T \rightarrow G \rightarrow H \rightarrow I \rightarrow J \rightarrow K \rightarrow L \rightarrow A \rightarrow B \rightarrow C \rightarrow D \rightarrow E \rightarrow F \rightarrow R \rightarrow S \]
A data packet is sent to the Preferred Parent.

A typical TSCH schedule
The ARQ function performs the re-transmission of a frame when a previous transmission failed.

A typical TSCH schedule

Preferred Parent (PP)
A data packet is sent to both Preferred & Alternative Parent.

A typical TSCH schedule
Considering that wireless medium is broadcast by nature.

- Any neighbor of a sender may overhear the transmission.
- Only the actual destination of the frame must ACK.

---

### A typical TSCH schedule

<table>
<thead>
<tr>
<th>Timeslot</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASN</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>

#### Channel Offsets

- **Shared Slot (EB)**
  - 4
  - 3
  - 2
  - 1
  - 0

#### Dedicated Slots

- **S⇒A (B)**
- **S⇒A (B)**
- **S⇒B (A)**
- **S⇒B (A)**

**Dedicated Slots**

- **S⇒A**
- **S⇒A**
- **S⇒A**
- **S⇒A**

---

**Promiscuous Overhearing**
A node discards the duplicated data packets.

<table>
<thead>
<tr>
<th>Timeslot</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
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</table>

A typical TSCH schedule

- Preferred Parent (PP)
- Alternative Parent (AP)
Step 2: PCE – Routing Plane (Alternative Parent Selection)
One possible option is to select the *Alternative Parent* as the *one having Common Ancestor*.
One possible option is to select the Alternative Parent as the one having Common Ancestor.

Many different variations/enhancements we have proposed over the years:
One possible option is to select the *Alternative Parent* as the *one having Common Ancestor*.

The default DODAG Topology

Preferred Parent (PP)

Alternative Parent (AP)
One possible option is to select the Alternative Parent as the one having Common Ancestor.
One possible option is to select the *Alternative Parent* as the *one having Common Ancestor*.
One possible option is to select the Alternative Parent as the one having Common Ancestor.
One possible option is to select the *Alternative Parent* as the *one having Common Ancestor*.

- Ladder (or DNA) pattern.
One possible option is to select the *Alternative Parent* as the *one having Common Ancestor*.
- Ladder (or DNA) pattern.

![Diagram of Alternative Parent Selection]

- **CAOF**
- **Preferred Parent (PP)**
- **Alternative Parent (AP)**
## Simulation Setup

Contiki OS & Cooja, Single-path, n-Disjoint, CA, ODeSe

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration</td>
<td>Topology</td>
</tr>
<tr>
<td>Until 5000 pkts</td>
<td>Mesh topology</td>
</tr>
<tr>
<td>Data traffic</td>
<td>Nº of nodes</td>
</tr>
<tr>
<td>1 pkt/ 15 sec</td>
<td>32</td>
</tr>
<tr>
<td>Routing protocol</td>
<td>Nº of layers (L)</td>
</tr>
<tr>
<td>RPL</td>
<td>5</td>
</tr>
<tr>
<td>Parent set size (N)</td>
<td>Nº of sources</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>$PS_{MC}$ size (M)</td>
<td>Link Quality</td>
</tr>
<tr>
<td>6</td>
<td>50%, 75%</td>
</tr>
</tbody>
</table>

### TSCH

<table>
<thead>
<tr>
<th>Scheduling</th>
<th>Centralized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timeslot length</td>
<td>10 ms</td>
</tr>
<tr>
<td>Nº of channels</td>
<td>1</td>
</tr>
<tr>
<td>Slotframe length</td>
<td>357 Timeslots</td>
</tr>
<tr>
<td>Slotframe length (N-Disjoint)</td>
<td>345 Timeslots</td>
</tr>
</tbody>
</table>

![Simulation Diagram](image.png)
Performance Evaluation
50% Link Quality: End-to-end Packet Delivery Ratio (6 hops)

Single-path (with retransissions)           Multi-path: 3 disjoint paths (+ retrans.)           Multi-paths (CAOF)
Performance Evaluation
50% Link Quality : End-to-end latency

Single-path (with retransissions)       Multi-path: 3 disjoint paths (+ retrans.)       Multi-paths (CAOF)
Performance Evaluation

50% Link Quality: Power consumption per algorithm
Simulation Results
50% Link Quality: Average number of relay nodes per data packet
Key Takeaways
Key Takeaways
Why PAREO and Multi-path approaches?
Key Takeaways
Why PAREO and Multi-path approaches?

Default RPL
(single-path) operation

Preferred Parent (PP)
Key Takeaways
Why PAREO and Multi-path approaches?

Default RPL (single-path) operation

PAREO + CAOF (multi-path) operation

Preferred Parent (PP)
Alternative Parent (AP)

et voilà
Key Takeaways
Why Common Ancestor pattern?

PAREO + CAOF
(multi-path) operation

et voilà

Preferred Parent (PP)
Alternative Parent (AP)
Key Takeaways
Why Common Ancestor pattern?

Default RPL (multi-path) operation

PAREO + CAOF (multi-path) operation

et voilà

Preferred Parent (PP)
Alternative Parent (AP)
Key Takeaways

Do not forget that this is Layer 3 solution (potentially in conjunction with Layer 2 for the scheduling)!

It can be applied to various PHY layer technologies!

Default RPL (multi-path) operation

PAREO + CAOF (multi-path) operation

et voilà

Preferred Parent (PP)

Alternative Parent (AP)
Default RPL (multi-path) operation

PAREO + CAOF (multi-path) operation

These work has been developed during the PhD period of Tomas Lagos, and during the Postdoc period of Remous-Aris Koutsiamanis, as well as during Research Internships of Tada, Julian, Ana.
Ongoing Work & Perspectives
Ongoing Work & Perspectives

1. PAREO Functions

► Pool of functions:
- Packet Transmission
- Automatic Repeat reQuest (ARQ)
- Replication
- Overhearing
- Elimination

► and more such as:
- Forward Error Correction (FEC) [1], [2]
- Packet (Re)Ordering (work-in-progress) → Juan-Cruz Pinero


To achieve Reliable and Available properties:

- Routing: Multi-path (RPL) ➔ Distributed / Adaptive!
- Resource Allocation: (Controller-based schedule) ➔ Centralized / STATIC!

Ongoing Work & Perspectives
2. Toward a Centralized Routing Approach

► To achieve Reliable and Available properties:
  - Routing: Multi-path (RPL)  ➔ Distributed / Adaptive!
  - Resource Allocation: (Controller-based schedule) ➔ Centralized / STATIC!

Towards fully centralized and adaptive entity (Controller):
  - Both for Routing and Scheduling, and why not even for Radio Channel Blacklisting decisions!

“A Centralized Controller for Reliable and Available Wireless Schedules in Industrial Networks”,
What about the modularity of the employed Stack?

The whole behavior of a node can be programmable.

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Global and programmable instructions
What about the modularity of the employed Stack.

The **whole behavior** of a node can be **programmable**.
Miscellaneous


Coordination de MOOC: coursera

- **09/2022 - **: “IoT Communications and Networks” (> 1000 enrolments).
- Link: https://www.coursera.org/learn/iot-communication-network
Outline of the MOOC:
- Week 1: Welcome & MAC Methods (i.e., TSCH)
- Week 2: 6TiSCH
- Week 3: IPv6 & 6LoWPAN
- Week 4: RPL

Educational Team:
- Remous-Aris Koutsiamanis
- Nicolas Montavont
- Georgios Z. Papadopoulos
- Géraldine Texier

Interviews from the industrial community:
- Pascal Thubert, Cisco Systems
- Thomas Watteyne, Analog Devices, Falco
- Rémi Dubaele, ENEDIS
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  - Alex Marquet
  - Remous-Aris Koutsiamanis

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  - Juan Sebastian Molina
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  - Fabián Antonio Rincon Vija
  - Guillaume Le Gall
  - Renzo Efraín Navas
  - Tomas Lagos Jenschke
  - Vasilios Kotsiou

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  - Ega Fosso
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  - Amaury Bruniaux
  - Dimitris Sourailidis
  - Matias Sambrizzi
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  - Eduardo Ingles Sanchez
  - Agustin Picard
  - Cristian Alderete
  - Chenyang Ji
  - Maurine Kersale
  - Julian Martin Del Fiore
  - Tadanori Matsui
  - Alexandros Mavromatis

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  - Carles Gomez
  - Xenofon Fafoutis, Atis Elsts
  - George Oikonomou, Theo Tryfonas
  - M. Gidlund, A. Mahmood
  - Dan Garcia-Carrillo, A. Skarmeta
  - R. Alami, R. Féraud
  - D. Dujovne, I. Alvarez-Hamelin
  - D. Zorbas, C. Douligeris

► Industrial Partners:
  - Pascal Thubert, Cisco
  - Dominique Poissonnier, TI
  - Samuel Cregut, Renault
  - Dominique Barthel, Orange
Reliable and Available
Low-Power Wireless Mesh Networks

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Backup Slides
Mandjet Platform
Mandjet Platform
IMT Atlantique - Campus of Rennes
Mandjet Platform
Architecture

- Solar Panels
- Converter/charger
- Batteries

Real time visualisation of consumption and production

EV Renting system
Mandjet Platform
1. Research

- Adaptation and interoperability protocols for smart grids:
  - e.g., 6LoWPAN, SCHC.

- Alignment of electricity consumption and production.
2. Education

CAMP
OSV
1 DÉC 2021

https://school.future-iot.org/camp-ev/
Prêt de véhicules légers électriques
Alternative Parent Selection: CAOF Strategies
Alternative Parent Selection
Common Ancestor Strategies

**Strict CA**
- Common Preferred Parent
  \[ PP(PP) = PP(AP) \]
- PP in the PS of the AP
  \[ PP(PP) \in PS(AP) \]

**Medium CA**
- Any Common Parent in the PSs
  \[ PS(PP) \cap PS(AP) \neq \emptyset \]

**Soft CA**
- Preferred Parent (PP)
- Temporary Parent (TP)
- Alternative Parent (AP)
- Parent Set (PS)

**ODeSe**