Software Defined Networking for the Industrial Internet of Things

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Bristol Research and Innovation Laboratory (BRIL), Toshiba Research Europe Ltd.
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Motivation and Aim

Key Contributions and Novelty

Recommendations

Future Research Agenda
Motivation and Aim
What is this thesis trying to achieve and why?
What is the Motivation Behind This Thesis?

- Toshiba has deployed extremely large AMI mesh networks in Japan (27 million smart metering nodes). This is a significant investment.
- The complexity of low-power wireless mesh means deployments tend to be...

![Diagram showing single-application, single-user, difficult to update, and limited in scalability.](image)
What is the Motivation Behind This Thesis?

Single-application, single-user.

- Difficult to configure/update.
- Limited in scalability.

Multi-application, multi-user.

- Easy to manage.
- Scalable!

The same benefits that SDN brings to traditional networks!
Imagine if computer programmers had to individually manage every CPU instruction and every memory block? Like the operating system on a computer, SDN hides low-level complexity. Data is managed on a per-flow basis using centrally computed rules.

This abstraction can then be used to provide virtual network slices, with a global interface allowing network functions to sit virtually on a SDN controller.
What is This Thesis Trying to Achieve?

- SDN has been successful in managing traditional networks.
  - Reduces capital and operational expenditure (CAPEX, OPEX)
  - Supports virtualisation techniques (e.g. Network Slicing + Network Function Virtualisation).
  - Helps network configurability through ‘programmable’ APIs on agnostic hardware.
  - Key Benefit: Simplifies network management and supports scalability.

- Management of IoT mesh solutions is highly complex.
  - Low-power wireless (often but not exclusively IEEE 802.15.4).
  - 2.4GHz and Sub-GHz 868 (UK/EU) introduce unique problems.
  - Interference management.
  - Radio Duty Cycling (power and/or regulation).
  - Constrained devices with half-duplex radios.
  - Multi-hop introduces multiple points of failure across any single path.
  - Key Challenge: Low-power mesh complexity limits its value as a scalable wireless solution.

Question: “Can SDN be applied in low-power multi-hop wireless?”
Background – Why is This Such a Challenge?

SDN is great in a wired network (e.g. data centre / cloud computing)...

... becomes very complicated in a narrowband, low-power, multi hop mesh!
Contributions and Novelty
SDN in Low-Power Multi-Hop Mesh Networks
Chapter 3: Reduction of SDN Control Signalling

Key contribution: 
μSDN can inject routing paths into packets via flowtable entries
Chapter 3: A Lightweight SDN Stack + Controller for LP-Mesh

Key contribution: Extendable SDN stack for academic research. Currently in use by a number of PhD students worldwide (I even met some at EWSN 2020)
Chapter 3: Evaluation of Overhead from SDN Control Signalling

**Key contribution:** Show that SDN overhead can be overwhelmingly reduced so that it has minimal effect on regular application traffic.

![Graphs and charts illustrating key performance indicators for RPL DAG and μSDN controller, including join times, end-to-end delay, packet delivery ratio, and radio duty cycling.]
Chapter 3: Demonstration of Per-Flow SDN Control

**Key contribution:** Explores a novel use-case showing how programmable rules can allow applications to make significant and dynamic network changes.
Key contribution: Shows that SDN overhead can be applied to the 6TiSCH stack, and was one of the first two works in this area - the other being Coral-SDN. (NB: The publication associated with this chapter appeared before the full uSDN paper as this contribution was at the direction of Toshiba, who wanted to make use of their proprietary 6TiSCH stack in 2017).
Chapter 4: Evaluation of SDN Signalling Overhead on 6TiSCH

Key contribution: Demonstrates how 6TiSCH has difficulty scaling to SDN control traffic overhead.
Chapter 4: 6TiSCH Track Allocation Algorithm for SDN Control Paths

Key contribution: Creates a uplink path for SDN control signalling by following the RPL route and allocating dedicated L2 resources.
Chapter 4: Demonstration of 6TiSCH Tracks for Network Slicing

Key contribution:
Shows that dedicated slicing, in general, can massively help mesh performance. As far as I’m aware, this is one of the only works on 6TiSCH tracks.
Chapter 5: Background - What are Concurrent Transmissions (CTs)?

- Usually when two nodes Tx at the same time, they will collide at the receiver
- If two nodes are well-synchronised the transmission can be reliably demodulated
- Can flood without worrying about contention!

1 0.5µs is half a chip period at 1Mchip/s... changes for different PHY layers. It's 250ns on the 2M Bluetooth PHY for example.
Synchronous Flooding (SF) allows the network to reliably send a packet across the mesh with minimal latency, using aggressive spatial, temporal and frequency diversity.
## Table 5.1: Summary of Advantages Enjoyed by SF Protocols

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology Agnostic</td>
<td>As flooding allows <em>one-to-all</em> broadcast, control signalling is reduced, mobility is supported, and there is no requirement for communications scheduling.</td>
</tr>
<tr>
<td>Minimal Latency</td>
<td>All communications are shortest-path by nature, and Back-to-Back (B2B) transmissions can allow a packet to be sent with theoretical minimum bounds on latency.</td>
</tr>
<tr>
<td>High-Reliability</td>
<td>Slot-by-Slot channel hopping, combined with minimal slot times, means an SF flood enjoys aggressive temporal, spatial, and frequency diversity.</td>
</tr>
<tr>
<td>Temporal Decoupling</td>
<td>The time-synchronised approach of SF allows guarantees to be made on the length of a flood, allowing floods to be scheduled alongside other network operations. This could, for example, allow a SF flood to be scheduled and encapsulated within a TSCH slot.</td>
</tr>
</tbody>
</table>
Chapter 5: An SF Layer For Robust, Minimal Latency SDN Control

**Key contribution:** This is world’s first solution that uses SF for minimal latency, highly-reliable SDN control signalling in multi-hop mesh, but Atomic, as a platform is considerably more. It also currently provides (unpublished) *Time Synchronisation, Multi-PHY Configuration, Multi-MAC Network Scheduling*, and is being used as the enabling framework for 5 current Toshiba research projects.
Chapter 5: Evaluation of SF Compared to Other SDN + MAC Solutions

Key contribution: Demonstrates the scalability of SF in comparison to other MAC solutions for multi-hop SDN architectures.

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Latency (ms)</th>
<th>PDR (%)</th>
<th>RDC (%)</th>
</tr>
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<tbody>
<tr>
<td>Atomic-SDN</td>
<td>34.0</td>
<td>100.00</td>
<td>1.34</td>
</tr>
<tr>
<td>µSDN-CSMA</td>
<td>33.94</td>
<td>99.58</td>
<td>100</td>
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<td>µSDN-ContikiMAC</td>
<td>340.42</td>
<td>96.45</td>
<td>3.76</td>
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<tr>
<td>SDN-WISE-CSMA</td>
<td>25.75</td>
<td>68.49</td>
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<tr>
<td>SDN-WISE-ContikiMAC</td>
<td>544.23</td>
<td>93.84</td>
<td>5.15</td>
</tr>
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</table>
Chapter 5: Experimental Evaluation of Atomic-SDN

Key contribution: Extensive evaluation under external interference has ‘battle-tested’ SF solutions. Atomic-SDN was the only team to place in both categories, and was the only one to achieve 100% PDR with longer packets (64B)

<table>
<thead>
<tr>
<th>Team</th>
<th>Rank in Category</th>
<th>Energy(J)</th>
<th>Reliability(%)</th>
<th>Latency(ms)</th>
</tr>
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<tbody>
<tr>
<td>01</td>
<td>1</td>
<td>1974.89</td>
<td>100.00</td>
<td>422.86</td>
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<tr>
<td>06 (ASDS)</td>
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<td>1818.82</td>
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<td>10</td>
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<td>12 (6TiSCH)</td>
<td>4</td>
<td>1164.83</td>
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<tr>
<td>11 (CRYSTAL)</td>
<td>5</td>
<td>1331.76</td>
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<tr>
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DepComp 2019 Data Collection

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<th>Team</th>
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<th>Reliability(%)</th>
<th>Latency(ms)</th>
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<td>447.59</td>
<td>30.89</td>
<td>3054.77</td>
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</table>

DepComp 2019 Data Dissemination
Key Results and Recommendations
Chapter 3:
• SDN control overhead can be managed, but not eliminated.
  • There needs to be more research into how SDN supports novel use-cases for wireless mesh (e.g. slicing/virtualisation, per-flow management, multi-tenancy, distributed control systems).

Chapter 4:
• The traditional view of SDN doesn’t scale well on TDMA schedules.
  • Novel ‘out-of-the-box’ approaches should be investigated (e.g. the Whisper ‘targeted’ approach is one. Coral-SDN is looking into OOB control planes).

Chapter 5:
• Synchronous Flooding ‘just works’.
  • CTs should be used to distribute (important) control signalling in multi-hop mesh. Always.
  • CTs can be used to ensure highly accurate multi-hop time synchronisation.

Bonus: Competitions drive innovation!
Future Research Agenda
Short Term

- **SF should be used to provide accurate time synchronisation and distribution centralised SDN control of 6TiSCH slotframes.**
  - SF is highly-synchronised. Generous guard times in IEEE 802.15.4-TSCH can be greatly reduced. This will improve overall network delay.
  - SF is extremely reliable, even under heavy WiFi interference. Control signalling will almost always get through.
  - SF is naturally *one-to-all* broadcast. We can communicate with the entire mesh in a single flood.
  - Recent work has shown SF over the BLE PHY layers. Higher rate physical layers can be used to rapidly configure the network or provide update services such as rolling out new firmware.
• Extend SDN architecture to address the multiple PHY layers available for low-power wireless IoT.
  • Focusing on one communication technology (i.e. IEEE 802.15.4) is highly restrictive and doesn’t represent the ‘real-world’ of wireless solutions used in the majority of scenarios.
  • Recent research has shown that Cross-Technology Communication (CTC) techniques are capable of 1kbps communication rates between heterogenous technologies*.
  • This could be used to explore control signalling in heterogenous IoT networks, with a view to providing a low-rate, low-level data plane, while SDN controllers make high-level decisions.
• Use SDN to support ‘Massive Mesh’ scale with Multi-MAC and Multi-PHY solutions (Software-Defined Massive Mesh).
  • Wide geographical areas mean the RF environment can vary considerably.
  • Multi user networks can have varying requirements for different applications.
  • No single solution is correct. MAC and PHY layers should be configurable according to policy set by a centralised controller.
  • This needs a common control signalling solution (i.e. OOB control signalling on another radio, or a SF solution).
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- External Collaborators at TU Graz: Carlo Alberto Boano and Markus Schuss.
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Additional Material: Current Work Examining Beating Effects in CTs

Concurrent Transmissions aren’t constructive interference! They are more like a big ball of wibbly wobbly beating effects....

The effect of CFO beating in CTs has been mentioned in a number of previous works:

A. Carrier offsets between two transmitters cause VERY noticeable beating effect.

~100 bits @ 256K = 400us