Poster: 4th Industrial Revolution: Toward Deterministic Wireless Industrial Networks

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Abstract

Critical applications such as industrial process control, smart grid and vehicle automation require networks which offer on-time data delivery and wire-like end-to-end reliability. This paper proposes to exploit path diversity to compensate for the lossy nature of the wireless medium. We introduce "Leapfrog Collaboration", a communication mechanism in which multiple copies of the same packet traverse the network on disjoint paths. Emulation results on Cooja show that, compared to single-path transmission, this technique reduces end-to-end delay by up to 28%, and jitter by up to 58%.

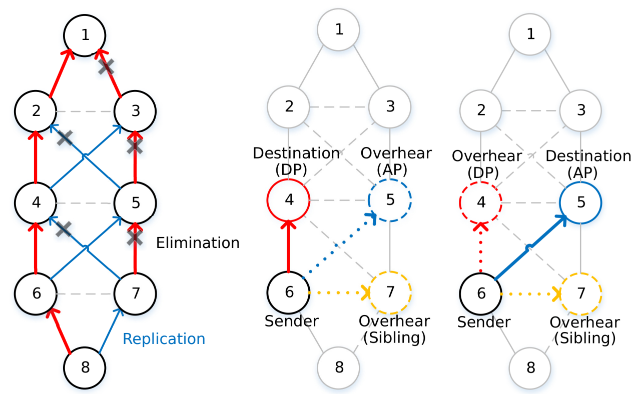
Keywords

Multi-path Routing Algorithm, Route Diversity, Determinism, Leapfrog Collaboration.

1 Motivation

Industry 4.0 re-uses Internet of Things (IoT) technology to simplify production chains, simplify deployment, and make the factory floor more flexible and adaptable. It heavily relies on deterministic networking technology, in which the network guarantees the information is carried with predefined and predictable delay, regardless of link quality and the network usage. One important goal for the network is to offer near-zero jitter. Current IoT technology builds on best-effort packet switched network, which introduces variable network delays because of retransmissions and queuing.

In 2016, a new version of the IEEE802.15.4 standard [1] was published. It introduces Time-Slotted Channel Hoping



(a) Packet Replication procedure. (b) Unicast to DP with Overhearing. (c) Unicast to AP with Overhearing.

Figure 1: Replication, Elimination and Overhearing operations.

(TSCH), a new Medium Access Control (MAC) mode designed for demanding industrial applications. In a regular TSCH network, a packet follows a multi-hop path between source and destination. Between some neighbors, when the link is poor, the same link-layer frame can be retransmitted multiple times. This increases end-to-end delay and jitter.

This paper proposes to enhance the forwarding mechanism: multiple copies of the same packet travel on disjoint paths through the network. This technique exploits path diversity. Because the first copy that reaches the destination is the one that counts, Leapfrog Collaboration lowers end-to-end delay and jitter.

2 Leapfrog Collaboration

IEEE802.15.4 TSCH offers a resource reservation mechanism which allows hop-by-hop scheduling when combined with the RPL [2] routing protocol. Since wireless is unreliable in nature, frames are retransmitted if no link-layer acknowledgment is received. Retransmissions increase delay, energy consumption and bandwidth. In some environments,

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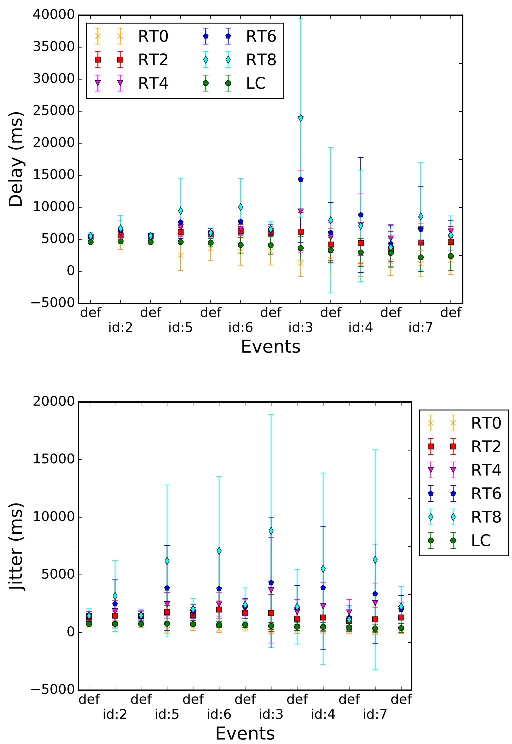

Figure 2: Average end-to-end delay *(top)* and jitter *(bottom)*.

losses can even be bursty, i.e. the link quality between two neighbors suddenly drops for some time. Consecutive retransmissions on the same frequency do not help in this case. RPL does come with a fail-over mechanism, but the delay to discover and use an alternate path can be long (in the order of seconds). Rather than recomputing the path, we duplicate packets along disjoint paths.

We use Fig. 1 to illustrate how Leapfrog Collaboration works. In this figure, node 8 wants to send data to node 1. Each node in the network maintains two parents: its Default Parent (DP) and Alternate Parent (AP). Leapfrog collaboration works best if the two paths of default parents ($8 \rightarrow 6 \rightarrow 4 \rightarrow 2 \rightarrow 1$ and $8 \rightarrow 7 \rightarrow 5 \rightarrow 3 \rightarrow 1$ in Fig. 1) are disjoint. It also works best if the default and alternate parents hear one another and if they have the same ancestor.

Each node on the Leapfrog Collaboration path does the same: it sends two copies of the same packet, one to the DP, one to the AP. Packets contain a unique counter, and node maintain a buffer of recently-heard (source IPv6 address, destination IPv6 address, counter) tuples. If a node received a packet already present in its buffer, it silently drops it (elimination). If, however, the packet is new, it forwards it to both DP and AP (replication).

From a TSCH point of view, each node has dedicated cells scheduled to its DP and to its AP. A node's sibling also schedules cells to overhear those cells. If, when listening to those cells, siblings hear a packet it has not heard before, it participates in Leapfrog Collaboration as if it had received it from its child.

By having multiple copies travel from source to destination in a "band" of nodes – rather than a single string of nodes –, latency and jitter are reduced. This is because latency/jitter are measured on the *first copy* of the packet. Leapfrog Collaboration exploits *path diversity* so the first copy arrives faster than if a single copy was sent in the first place.

3 Performance Evaluation

Setup. We implement Leapfrog Collaboration on Contiki OS[1] and run simulations on Cooja, with emulated Zolertia Z1[2] nodes. We use the topology from Fig. 1, deployed on a $40\ m \times 10\ m$ area. Node 8 transmits 1 data packet every 10 seconds to node 1. Transmission power of all nodes is set to 0 dBm. We use the RPL protocol to construct the routing structure. We use a single IEEE802.15.4 TSCH slotframe with 101 timeslots. We compare the performance of Leapfrog Collaboration against that of the default RPL protocol (i.e. a single copy travels through the network). On the base implementation, we vary the maximum number of link-layer retransmissions: RT2 means that the TSCH implementation will re-transmit at most twice in case no link-layer acknowledgment is received.

Delay. Fig. 2 shows the average end-to-end delay[3] for both Leapfrog Collaboration and the base TSCH implementation (RTx, where x is the maximum number of link-layer retransmissions). Leapfrog Collaboration reduces the end-to-end delay when compared to the retransmission-based approaches of IEEE802.15.4-TSCH (i.e. RT2, RT4, RT6 and RT8). Indeed, it decreases by up to 28%, 41%, 46% and 54%, respectively.

Jitter. Jitter is calculated as the time of consecutive packet inter-arrival from the source node to the destination. Fig. 2 shows the average end-to-end jitter. The results confirm that packet retransmissions impact jitter: the higher the retransmissions, the higher is the jitter (i.e. RT8 shows results over 5000 ms). Leapfrog Collaboration exhibits low (i.e. 600 ms) and stable jitter throughout the simulation lifetime. It reduces jitter by up to 58%, 71%, 77% and 84% when compared to RT2, RT4, RT6 and RT8, respectively.

4 Conclusion

Industry 4.0 is considering standard IoT technology to replace or extend wired networking systems. Recent IEEE802.15.4 changes provide a framework for QoS, but delays are hard to guarantee in lossy packet switched network. This poster introduces Leapfrog Collaboration: sending multiple copies of the same packet on disjoint paths lowers latency and jitter by exploiting path diversity, a statement which is confirmed by simulation results.

5 References

[1] IEEE Standard for Low-Rate Wireless Personal Area Networks (LR-WPANs). *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, April 2016.

[2] T. Winter, P. Thubert, A. Brandt, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, J. Vasseur, and A. R. RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks. RFC 6550, IETF, 2012.

[1] `http://www.contiki-os.org/`

[2] `http://zolertia.io/z1`

[3] Delay and jitter are calculated on successful packet receptions.