Competition: Sparkle — Energy Efficient, Reliable, Ultra-low Latency Communication in Wireless Control Networks

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Abstract

Wireless Sensor Networks is undergoing rapid development in the past decade. Yet its application in real-time systems is still immature. One of the main causes of this status is due to the lack of a deterministic end-to-end protocol that achieves high energy-efficiency, high reliability and low latency in communication simultaneously. This document describes Sparkle, a suitable deterministic protocol for Wireless Control Networks. It is also a competitor for the dependability competition of EWSN 2016. A detailed description and evaluation of the Sparkle protocol has been published in the proceedings of EWSN 2014.

Keywords

Wireless control network, End-to-end protocol

1 Introduction

Wireless sensor networks (WSN) offer great potential in industrial automation and control applications by 1) cutting off huge cost of wiring, 2) offering high flexibility in deployment, and possibility for mobility, 3) saving energy by applying low-power communication and tiny sized sensors, and 4) offering fault tolerance with ad-hoc network structure and large number of sensors. However, the generally strict quality-of-service (QoS) requirements of these applications (high energy-efficiency, high reliability and low latency) are very challenging, given the intrinsically unreliable communication of WSN. Despite the fact that some pioneering works in academia and a few industrial standards have appeared, we are still in need of a deterministic end-to-end protocol that achieves high energy-efficiency, high reliability and low latency in communication simultaneously.

Recently, the Glossy protocol [1] showed the possibility of obtaining deterministic low latency, high reliability and high synchronization precision simultaneously by applying the technology of constructive interference (CI), i.e. a number of nodes transmit the same packet at roughly the same time so that the signals add up constructively at the receiver. These features match the requirements of control networks very well. Based on Glossy, we proposed *Sparkle* [3], a periodic multi-loop control network where each control loop is mapped into one or more communication flows. The novelty of Sparkle is that we "control" each end-to-end flow based on runtime feedbacks, with the goal that the QoS metrics of the flow satisfy given requirements or are optimized.

Specifically, we showed that by combining topology control and transmission power control, the flow metrics of reliability, energy consumption and latency can be further improved simultaneously, compared to Glossy. We proposed a novel technique for topology control, *WSNShape*, which uses the *capture effect* [2] to find a number of reliable paths between the source and the destination of a flow and then activate nodes on one or more of these paths. It greatly reduced energy consumption and also improved end-to-end reliability and latency with a high probability. Additionally, we experimentally showed that the transmission power also affected the QoS metrics significantly. The Glossy protocol without WSNShape may not be reliable enough for control networks.

Based on these findings, we designed the "controller" of Sparkle – *PRRTrack*, which adaptively switches between operation modes of different transmission powers and WSNShape levels. Experiments on real-world testbeds showed that the requirement on reliability is satisfied, the latency is reduced, and the energy consumption is greatly improved over Glossy.

2 The Design of Sparkle

Sparkle employs a protocol similar to TDMA. The architecture makes independent QoS control on each end-to-end flow possible.

2.1 Frame Structure

A Sparkle frame is composed of a *sync slot*, a number of *data slots* and zero or one *control slot*. In each slot, a flooding is performed with a source node, a transmission power and a set of participating nodes.

The purpose of the sync slot is to obtain network-wide time synchronization, in which an authority node floods a short sync packet over the network with the Glossy protocol. The network-wide time synchronization is a prerequisite for the data communication in Sparkle. The next data slots are used for the communication of arbitrary flows. Different

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flows may have different period length, dependent on the requirement of the control systems. The control slot is used for QoS control of the flows.

2.2 Topology Control with WSNShape

Control networks normally feature end-to-end communication, which is a special case of the one-to-all communication of Glossy. Sparkle finds a *stripe* of nodes between the source and destination for each flow, and only performs Glossy flooding among these nodes. In this way, it significantly reduces energy consumption. This process is performed by our novel WSNShape topology control.

Path Identification The most important step of WSNShape is path identification, i.e. to find the reliable paths between the source and destination of a flow. This is done by sending a special *path-ident* packet from the source node. An intermediate node may hear the packet due to the capture effect. The node sets its bit on the packet and relays it for once. At the destination, the packet can be used to reconstruct a reliable path from the source to the destination.

WSNShape Protocol After we have identified the reliable paths, we are ready to utilize them to improve the QoS with the WSNShape protocol. The destination node combines a number (parameter C) of the most commonly identified paths to form a stripe. In case the stripe has been changed, it floods the new stripe in the form of bit map in the next control slot for the opposite flow.

2.3 PRRTrack: Controlling Energy Consumption and Reliability

A useful control system normally requires that each flow (control loop) has latency below and reliability above presets. PRRTrack is a component of Sparkle that adaptively switches between different operation modes, with the goal of minimizing energy consumption while meeting the reliability requirement. In case the reliability requirement cannot be satisfied by any of the modes, PRRTrack achieves the best-effort performance by keeping a flow operate in the most reliable mode. The testbed evaluation shows that PRRTrack effectively achieves its design goal together with the additional advantage of improved latency.

2.3.1 The Design of PRRTrack

The main idea of PRRTrack is simple: if the current mode satisfies the reliability requirement, it tries to find a more energy-efficient one, otherwise it tries to find one that satisfies the reliability requirement. Given the model of relative energy efficiency of our various modes, the process to find a more energy-efficient mode is straightforward. But on the other hand, since no deterministic model of the relative reliability is available, the process to find a mode satisfying the reliability requirement is basically trial-and-error.

The control logic of PRRTrack is realized at the destination node of a flow. It performs two activities: first, it maintains the recently identified paths for WSNShape; second, it keeps track of the *current PRR* by calculating the reception rate of the recent data packets of a flow. Also, in the manner of feedback control, it gives proper commands of mode switch based on the difference between the current PRR and the reliability preset.

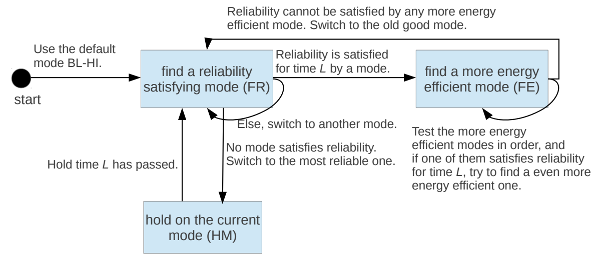

Figure 1. The mode switch process of PRRTrack.

The mode switch process of PRRTrack is illustrated in Fig. 1. We only switch among the four modes BL-HI (high tx power plus all nodes active), BL-LO (low transmission power plus all nodes active), NS-2 (high transmission power plus WSNShape with $C = 2$) and NS-ALL (high transmission power plus WSNShape with $C = \infty$).

2.4 Interference Mitigation

To add to the capability of interference mitigation, Sparkle cyclically uses multiple channels in each communication slots.

3 Performance

To evaluate Sparkle, we compare its performance to that of Glossy. Sparkle can keep up with the reliability requirement of 90% while adaptively switching to the most low-energy mode, while the reliability of Glossy may fall below the preset (c.f. [3] for the detail). The energy consumption and latency results of two representative flows in the Piloty testbed are shown in Tab. 1. The energy saving of Sparkle is huge—it uses only 22% and 13% of that of Glossy. The control overhead amounts for about 1/5 of the energy consumption. Additionally, Sparkle also improves the average end-to-end latency by about 10%.

Table 1. The energy consumption and latency of Sparkle vs. Glossy. $\mathrm{Energy_d}$ is the energy consumption of data slots. $\mathrm{Energy_c}$ is that of control slots.

	Glossy (Sparkle with fixed mode BL-HI)			Sparkle (PRRTrack)		
	$\mathrm{Energy_d}(J)$	$\mathrm{Energy_c}(J)$	Latency(ms)	$\mathrm{Energy_d}(J)$	$\mathrm{Energy_c}(J)$	Latency(ms)
flow $n_{26} \leftrightarrow n_{63}$	1008.27	0	18.09	196.21	24.11	16.15
flow $n_{16} \leftrightarrow n_{61}$	1009.68	0	16.11	109.21	23.17	14.45

4 Conclusion

We have presented Sparkle, a communication network for periodic multi-loop control systems with high reliability, very low energy consumption, as well as near-optimal latency. However, its performance comparison with the state-of-the-art reliable communication protocols of WSN is missing. We hope to have a good view on this by participating in the dependability competition of EWSN 2016.

5 References

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