Towards Wireless Industrial Control over 6TiSCH Networks

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ABSTRACT

IETF 6TiSCH is emerging as a promised open-standard for industrial internet of things (IIoT). With employing Time Slotted Channel Hopping (TSCH) mode, 6TiSCH can meet critical requirements in the industrial sector such as reliability, determinism and real time. 6TiSCH is currently focusing on monitoring applications. This paper considers its applicability in industrial control, in which sensor and actuator are coexistent in the network. We first investigate applicable wireless sensor-actuator models based on 6TiSCH. Then, an efficient data transmission scheme between sensor and actuator is proposed. Through simulation results, we show that our solution achieves a significant improvement in terms of end-to-end latency and energy consumption compared to the bursty transmission in the 6TiSCH networks.

KEYWORDS

Internet of Things, Industrial control, Sensor-Actuator, 6TiSCH, IEEE 802.15.4e TSCH, 6top

1 Introduction

Wireless sensor and sensor-actuator networks are playing important roles in industrial applications with low operational cost, pervasive communication, and energy efficiency [1]. In order to meet critical requirements of the applications, several standards such as WirelessHART [2] and IEEE802.15.4 TSCH [3] have introduced. The core of these standards is Time Synchronized Channel Hopping (TSCH) which is based on time synchronization and channel hopping to achieve ultra-low power operation and high reliability [4]. In 2013, the IETF working group, named 6TiSCH, was created to investigate IPv6 connectivity over the TSCH. In the 6TiSCH networks, sensor nodes are synchronized and follow a common schedule. The schedule consists of a slotframe structure that is constructed from a repeated sequence of timeslots and a set of available communication channels (i.e., up to 16 channels).

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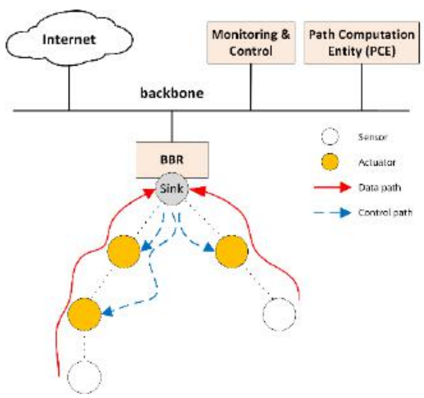
The 6TiSCH working group has defined an operation sub-layer, called 6top, to build and maintain schedule and bind IEEE 802.15.4 TSCH with other IETF upper layers (i.e., IETF 6LoWPAN [5], RPL [6], CoAP [7]). Likewise, the group is also working on a set of protocols for setting up a schedule in distributed approach with various scheduling functions [8].

In the literature, a number of applications of 6TiSCH are present. However, most of them only consider monitoring applications [9] [10] [11]. How to use the 6TiSCH networks in control applications remains an unresolved issue. Authors in [12] [13] showed their efforts to explore the applicability of 6TiSCH to control loop system in a very first step. They used a simple linear topology to implement the testbeds and measure the network performance with various scenarios.

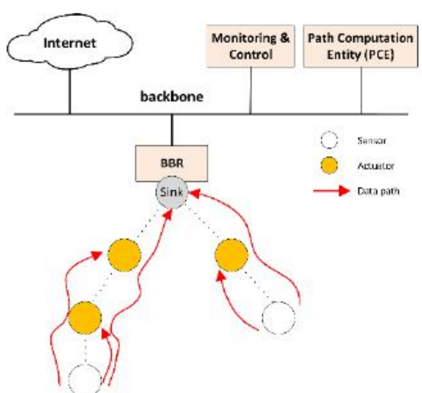
Inspired by these works, in this paper, we outline potential wireless sensor-actuator models over the 6TiSCH networks, that are partial-automated and fully-automated architectures. In the case of partial-automated architecture, all sensor nodes in the network send upstream data to the sink node. A center entity processes the data and controls actuator nodes through downstream commands. With the latter architecture, the sensor nodes send data directly to the actuator node for the fast reaction. However, in a dynamic network, the sensor nodes can leave and join frequently [4], thereby causing the unstable transmissions. Data packet from the sensor is even lost or cannot reach target actuator in a timely manner. Consequently, the reliability and real time is not guaranteed. Moreover, with many actuator nodes in the network, a sensor node may carry out different data transmissions which have the same data content. This may lead to a wasted network bandwidth and the increase of end-to-end latency as well as energy consumption. To overcome such issues, we propose an efficient data transmission scheme between sensor and actuator in the fully-automated architecture. Our solution enables an actuator node can obtain data packet, which is useful for the node, despite that the node is not the destination of the packet. In this way, a data packet can be used by multi actuator nodes, therefore the network bandwidth is reduced. Moreover, when a certain data packet is not sent to the actuator node on time, it can be replaced by data packets from other sensor nodes immediately. Through the simulation results, we show that the proposed scheme achieves a significant improvement in terms of end-to-end latency and energy consumption, compared to the burst traffic scenario.

The remainder of this paper is organized as follows: Section 2 presents wireless sensor-actuator models over the 6TiSCH networks. In Section 3, the details of the proposed transmission scheme are provided. Section 4 reveals the performance through a simulation. Lastly, in Section 5, the conclusion is drawn.

2 Wireless Sensor-Actuator Models over 6tisch Networks



(a)



(b)

Figure 1: Sensor-Actuator models over 6TiSCH networks with partial-automated architecture (a) and fully-automated architecture (b).

The 6TiSCH networks employ the IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) to build a Destination Oriented Directed Acyclic Graph (DODAG). In the RPL, each node selects its one or more parents and acts as a relay toward the sink node. In case of routing back the node, the sink uses source routing in the so-called Non-Storing Mode to realize the network topology [14]. RPL in 6TiSCH commonly supports for routing information, in which all sensor nodes collect and send sensing data to the sink node through routing paths. The main application is monitoring without doing any action. To extend functions of 6TiSCH, we refer to wireless sensor-actuator networks (WSAN) architectures [15]. WSAN supports to sense and react to the environment through actuator nodes. Typical network architectures of WSAN are categorized to partial-automated and fully-automated. On the basis of these architectures, we outline sensor-actuator models over the 6TiSCH networks as shown in Figure 1.

We consider that all sensor and actuator nodes in the 6TiSCH networks are able to participate in routing tasks. In the partial-automated architecture, the sensor nodes route sensing data to the sink that connects with the backbone router (BBR). The Monitoring and Control component collects and processes the data, and sends control commands to the actuator nodes through their IP addresses. The control communication can exploit CoAP protocol which is the lightweight Client-Server interaction model and integrated officially in the application layer of 6TiSCH stack [16].

In the case of fully-automated architecture, sensing data is sent directly to actuator node. The actuator node processes the data locally and makes the decision to react to the environment. Without using central entities (i.e., sink, BBR, Monitoring and Control component), the fully-automated approach enables a rapid response to the environment changes. Therefore, it is more suitable for real-time control applications. Moreover, in the architecture, a sensor node can send its data to many actuator nodes, depending on system and application requirements.

3 Proposed Sensor-Actuator Transmission in Fully-Automated Architecture

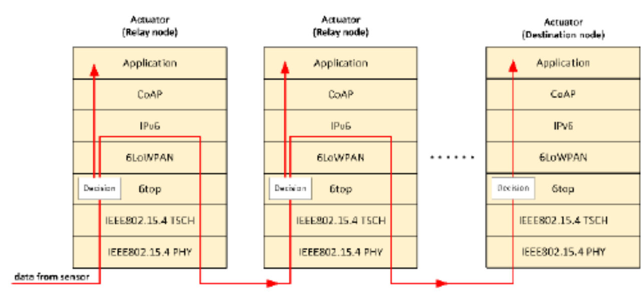


Figure 2: Sensing data packet traversing actuator nodes.

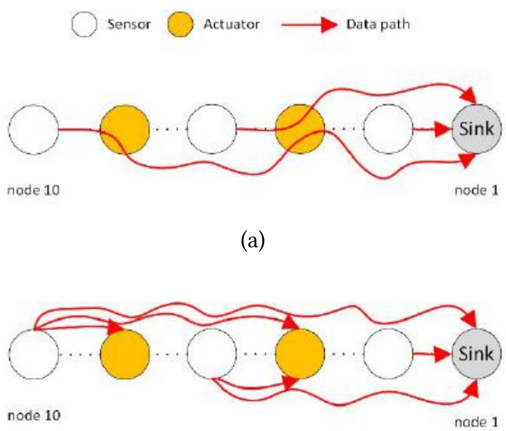
In this section, we describe an efficient transmission scheme to overcome redundant as well as unstable transmission problem of the fully-automated architecture in the 6TiSCH networks.

We propose that the packet, transmitted from a sensor node to its destination actuator node, can be used by relay actuator nodes for their control application. These actuator nodes belong to routing path of the packet as shown in Figure 2. In this way, a data packet can reach many actuator nodes without multi transmissions. In our solution, each data packet contains the additional significant information such as data type, location or ID of the sensor which generates the data. We propose a new Decision module in 6top layer. The module has responsibility to process the additional information and decide that whether the data packet is useful for the node or not. The packet will be forwarded to the application layer for further processing once it is necessary. The operation of Decision module does not affect the routing process for the packet at 6LoWPAN and IPv6 layer. The packet continues to be transmitted to its destination through other relay nodes based on the destination actuator's IP address. Furthermore, with the proposed approach, an actuator node can obtain redundant data packets for backup if it cannot receive packets from its desired sensors on time. The backup data packets can be from specified sensors recognized through ID in the additional information or certain sensors which have similar characteristics with the desired sensors such as same location and same sensing data type.

4 Performance Evaluation

This section presents the performance evaluation of the proposed solution through the simulation.

SIMULATION SETUP



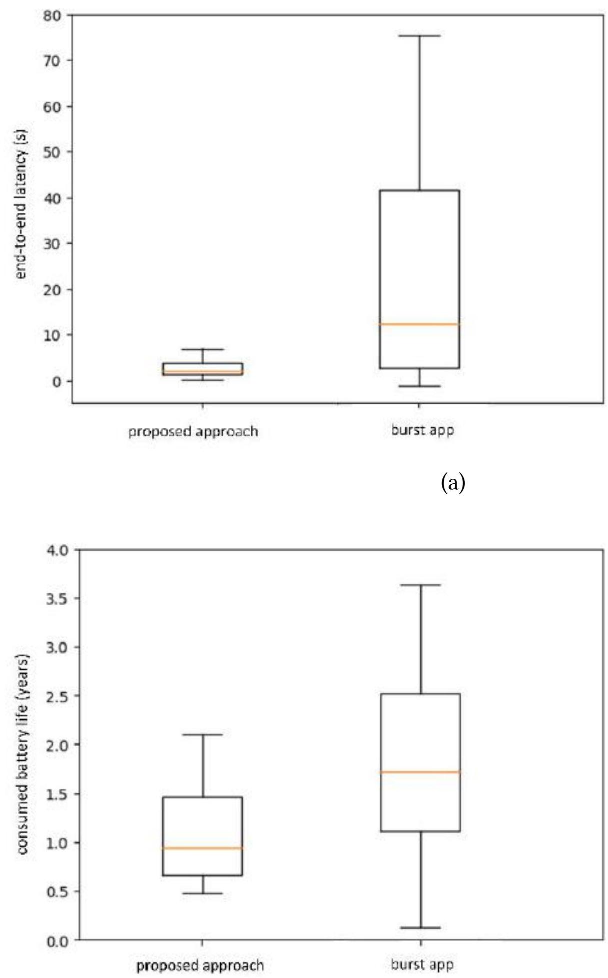
(a)

(b)

Figure 3: **Simulation setup with the proposed approach (a) and the burst traffic scenario (b).**

To evaluate the performance of our solution, the 6TiSCH simulator [17] which is an open-source implementation written in Python and developed by members of the 6TiSCH WG, is employed. We set up 10 nodes in a linear network as shown in Figure 3. The nodes are distributed in an area of 500m x 500m. In particular, node 8, 6, 4, 2 are actuator nodes, node 1 is the sink and also acts as an actuator node, while other nodes are sensor nodes. The timeslot duration is 10ms, and a slotframe contains 101 timeslots. The Minimal Scheduling Function (MSF) [18] is used as a main scheduling function in the simulation. The simulation results are presented based on an average of 100 simulation runs with a 95% confidence interval, in which the number of cycles per run is 1000. In the case of proposed approach, each sensor sends 1 data packet periodically with 1s interval to destination node 1. The relay actuator nodes, belonging to the packet routing path, can obtain the packet for routing support or use at the application layer. We implement Decision module in 6top layer and enable all data packets sent from sensor nodes to be useful for all actuator nodes. To highlight the advantages of our solution, we compare the proposed transmission scheme with the burst traffic scenario in 6TiSCH, in which each sensor node can send different packets to actuator nodes at the same time. We measure the network performance in terms of end-to-end latency and energy consumption.

SIMULATION RESULTS



(a)

(b)

Figure 4: Performance evaluation in terms of end-to-end latency (a) and energy consumption (b).

In Figure 4a, the end-to-end latency performance is illustrated. As it can be observed, our solution outperforms the burst traffic scenario with only average 2s latency. With the high packet transmission rate in the burst traffic, the scheduling function cannot meet a sufficient quantity of allocated cells in a timely manner for the packet transmissions. Consequently, the packets have to be placed in the queue buffer to wait for their transmission turn.

Figure 4b shows a comparison of energy consumptions according to average consumed battery lifetime of each sensor node after a simulation run. The higher number of packet transmissions requires the more number of transmission cells, which leads to the increase of energy consumption in the network [19]. Therefore, the energy consumption of the sensor node applying our solution is significantly lower than the burst traffic approach.

5 Conclusions

This paper shows our effort to outline sensor-actuator models in the 6TiSCH networks with partial- and fully-automated sensor-actuator architectures. Moreover, we also propose an efficient sensor-actuator transmission scheme to overcome the restrictions in the fully-automated architecture. Through the simulation, the results show that the proposed scheme achieves a significant improvement in terms of end-to-end latency and energy consumption, compared to the burst traffic scenario.

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