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IoT Network Digital Twins modeling using Petri-Nets

Mehdi Kherbache¹, Moufida Maimour¹, Eric Rondeau¹

CRAN Laboratory, Université de Lorraine, CNRS, UMR 7039, Campus Sciences, BP 70239, F-54000
Nancy, France

`mehdi.kherbache@univ-lorraine.fr`, `moufida.maimour@univ-lorraine.fr`,
`eric.rondeau@univ-lorraine.fr`

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1 Introduction

IoT (Internet of Things) is a key component of Industry 4.0, a term that refers to the fourth industrial revolution characterized by the integration of digital technologies into manufacturing and other industrial processes. This integration has given rise to Industrial IoT (IIoT) networks, which are used to create smart factories to optimize production processes, thus, reducing cost, improving efficiency and enabling data-driven decision making [9]. To meet the requirements of IIoT such as reliability, real-time performance, energy efficiency, among others [1], Digital Twins (DT) are a strong potential solution. A DT is a virtual replica of a physical system that reflects its properties, condition and behavior by means of models, information and data [12], enabling its control with the aim of increased performance and reduced costs.

Recently, the networking industry has shown great interest in Digital Twins due to their immense potential in improving the field [2]. Specifically, Network Digital Twins (NDTs) have emerged as a key focus in this regard. However, one of the various challenges that need to be addressed is the network data modeling [14]. In [8], a simplified modeling for data-center networks by retrieving information from configuration files and devices status is presented. Graph Neural Networks (GNN) are used to construct the NDT in [2, 7], while [15] employ knowledge graphs for NDT modeling.

Petri-nets (PNs) are widely used to model and simulate the behavior of discrete systems due to their ability to express a system's characteristics and behavior through strict mathematical and intuitive graphical expressions. They have been used for a long time in computer networks, in the context of Local Area Networks (LAN) [3], for protocol verification [4], for evaluating Networked Control Systems [5], in wireless applications for active product security [16] but also for network security [13].

In this work, we provide a proof of concept on using PNs to model the IoT network in the context of NDTs. The constructed model allows the prediction of network failure in advance and can serve as an anomaly detection module of the NDT.

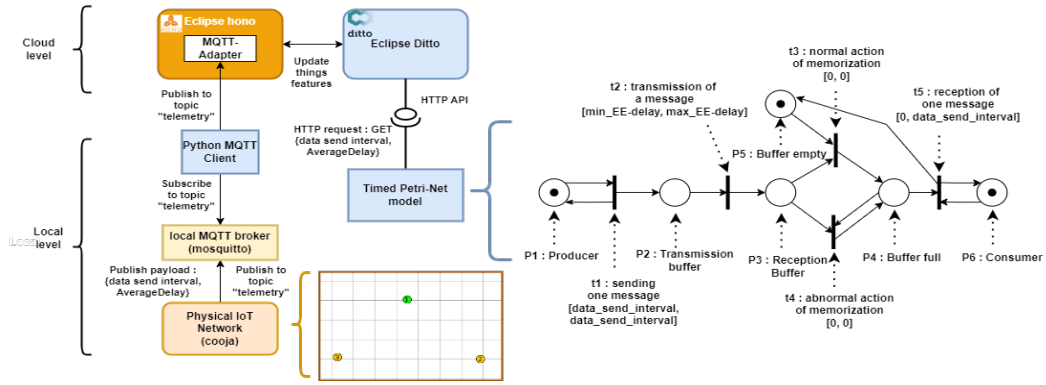


FIG. 1 – NDT architecture with Timed Petri-nets

2 NDT modeling with Petri-nets

Timed Petri-Nets (TPN) are an extension of PNs that add timing constraints to transitions. We employ this formalism in the context of NDTs to model the IoT network, as Figure 1 illustrates. Our NDT architecture is depicted along with the TPN model adopted. At the local level, the IoT network is simulated using Cooja [10], and Message Queuing Telemetry Transport (MQTT) is used as the application protocol to send telemetry to the NDT. An MQTT client implemented in Python forwards all the telemetry received by a local MQTT broker to the NDT. On the cloud level, Eclipse Hono [6] acts as a connectivity layer supporting various protocols (MQTT, CoAP, HTTP) for IoT devices, while Eclipse Ditto [6] is an open source framework for creating digital IoT twins called "*things*". A thing in Ditto is a data structure organized into attributes and features, and an HTTP API (Application Programming Interface) is provided to retrieve the things state.

The right side of figure 1 presents the TPN model that we implemented using SNAKES [11]. We adopted a producer-consumer model to reflect an IoT network with multiple sources (producer place P1) and one destination (consumer place P6). The rest of the model elements (places, transitions) and their signification are included in the figure. Transition t3 represents successful packet reception while t4 models packet loss which we use to calculate the predicted Packet Delivery Ratio (PDR). The parameters of the model are : the nodes data send interval (DSI) is t1 delay, the network's end-to-end delay (EE-delay) is t2 delay, t3 and t4 with null delays, and t5 delay is between 0 and the DSI. Each node sends the DSI and the EE-delay periodically to update its digital IoT twin (thing) features in Eclipse Ditto, which are then retrieved by the TPN model via the HTTP API.

The TPN model provides an efficient, simplified way of predicting PDR of the network based on the nodes DSI and the network's EE-delay, depicted as Action 1 in Figure 2. In addition, it can serve as an anomaly detection module in the NDT by comparing between the IoT network's PDR and the predicted PDR by the TPN model (Action 2 in Figure 2). The model was tested on a scenario with two transmitter nodes and one receiver. The DSI of the transmitter nodes were set to 500 ms, 200 ms and 100 ms respectively, while the period of publishing telemetry was 20 times the DSI. The published average delay was the mean delay of all the values in this interval. After learning the network's EE-delay, the TPN model is launched to predict the PDR. The bar chart depicted in the center of Figure 2 highlights the accuracy of the prediction where the IoT PDR is compared to the PDR calculated by the TPN model, the error margin should be taken into consideration since the TPN model does not mirror perfectly the real IoT network. The presented results showcase the model's utility as it is demonstrated by its ability to act as a lightweight simulation tool for the NDT, providing a platform to run what-if scenarios, anticipate possible network failure in terms of packet loss and detect anomalies. Therefore, the NDT can send control commands to adjust the nodes' DSI in order to maintain high reliability and trigger an alert when an anomaly is detected, allowing for prompt action to be taken.

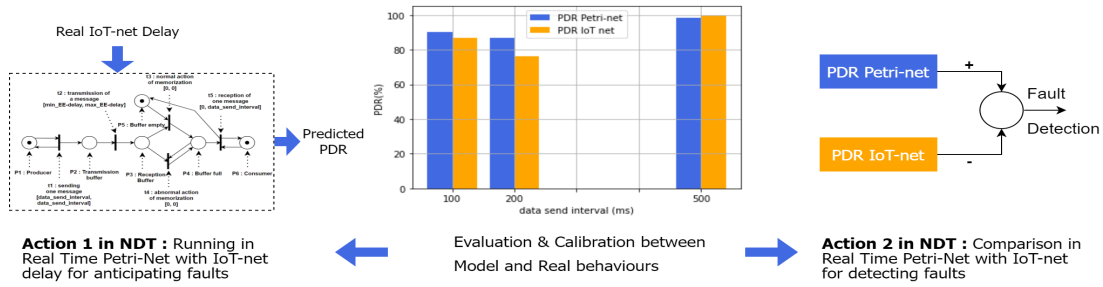


FIG. 2 – NDT functions with the adopted TPN model.

3 Conclusion and future work

This work explored the usage of Petri-nets to model the IoT's behavior in the context of NDTs. A TPN producer-consumer model was adopted to demonstrate its utility as a simulation asset of the NDT allowing faults anticipation and detection in terms of PDR, the accuracy of PDR prediction for a small scale network was demonstrated. Future work will consist in testing with a real IoT testbed (IoT-LAB) and focus on extending the model to include more parameters and networking scenarios for better network behavior mirroring.

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