

**Dissertation title:**

**Scheduling & Routing Time-triggered Traffic in Time-sensitive Networks**

**Naresh Ganesh Nayak**

The application of recent advances in computing, cognitive and networking technologies in manufacturing has triggered the so-called fourth industrial revolution, also referred to as Industry 4.0. Smart and flexible manufacturing systems are being conceived as a part of the Industry 4.0 initiative to meet the challenging requirements of the modern day manufacturers, e.g., production batch sizes of one. The information and communication technologies (ICT) infrastructure in such smart factories is expected to host heterogeneous applications ranging from the time-sensitive cyber-physical systems regulating physical processes in the manufacturing shopfloor to the soft real-time analytics applications predicting anomalies in the assembly line. Given the diverse demands of the applications, a single converged network providing different levels of communication guarantees to the applications based on their requirements is desired.

Ethernet, on account of its ubiquity and its steadily growing performance along with shrinking costs, has emerged as a popular choice as a converged network. However,

Ethernet networks, primarily designed for best-effort communication services, cannot provide strict guarantees like bounded end-to-end latency and jitter for real-time traffic without additional enhancements. Two major standardization bodies, viz., the IEEE Time-sensitive Networking (TSN) Task Group (TG) and the IETF Deterministic Networking (DetNets) Working Group are striving towards equipping Ethernet networks with mechanisms that would enable it to support different classes of real-time traffic. In this thesis, we focus on handling the time-triggered traffic (primarily periodic in nature) stemming from the hard real-time cyber-physical systems embedded in the manufacturing shopfloor over Ethernet networks. The basic approach for this is to schedule the transmissions of the time-triggered data streams appropriately through the network and ensure that the allocated schedules are adhered with. This approach leverages the possibility to precisely synchronize the clocks of the

network participants, i.e., end systems and switches, using time synchronization protocols like the IEEE 1588 Precision Time Protocol (PTP). Based on the capabilities of the network participants, the responsibility of enforcing these schedules can be distributed. An important point to note is that the network utilization with respect to the time-triggered data streams depends on the computed schedules. Furthermore, the routing of the time-triggered data streams also influences the computed transmission schedules, and thus, affects the network utilization. The question however remains as to how to compute transmission schedules for time-triggered data streams along with their routes so that an optimal network utilization can be achieved.

We explore, in this thesis, the scheduling and routing problems with respect to the time-triggered data streams in Ethernet networks. The recently published IEEE 802.1Qbv standard from the TSN-TG provides programmable gating mechanisms for the switches enabling them to schedule transmissions. Meanwhile, the extensions specified in the IEEE 802.1Qca standard or the primitives provided by OpenFlow, the popular southbound software-defined networking (SDN) protocol, can be used for gaining an explicit control over the routing of the data streams. Using these mechanisms, the responsibility of enforcing transmission schedules can be taken over by the end systems as well as the switches in the network. Alternatively, the scheduling can be enforced only by the end systems or only by the switches. Furthermore, routing alone can also be used to isolate time-triggered data streams, and thus, bound the latency and jitter experienced by the data streams in absence of synchronized clocks in the network.

For each of the aforementioned cases, we formulate the scheduling and routing problem using Integer Linear Programming (ILP) for static as well as dynamic scenarios. The static scenario deals with the computation of schedules and routes for time-triggered data streams with a priori knowledge of their specifications. Here, we focus on computing schedules and routes that are optimal with respect to the network utilization. Given that the scheduling problems in the static setting have a high time-complexity, we also present efficient heuristics to approximate the optimal solution. With the dynamic scheduling problem, we address the modifications to the computed

transmission schedules for adding further or removing already scheduled time-triggered data streams. Here, the focus lies on reducing the runtime of the scheduling and routing algorithms, and thus, have lower set-up times for adding new data streams into the network.