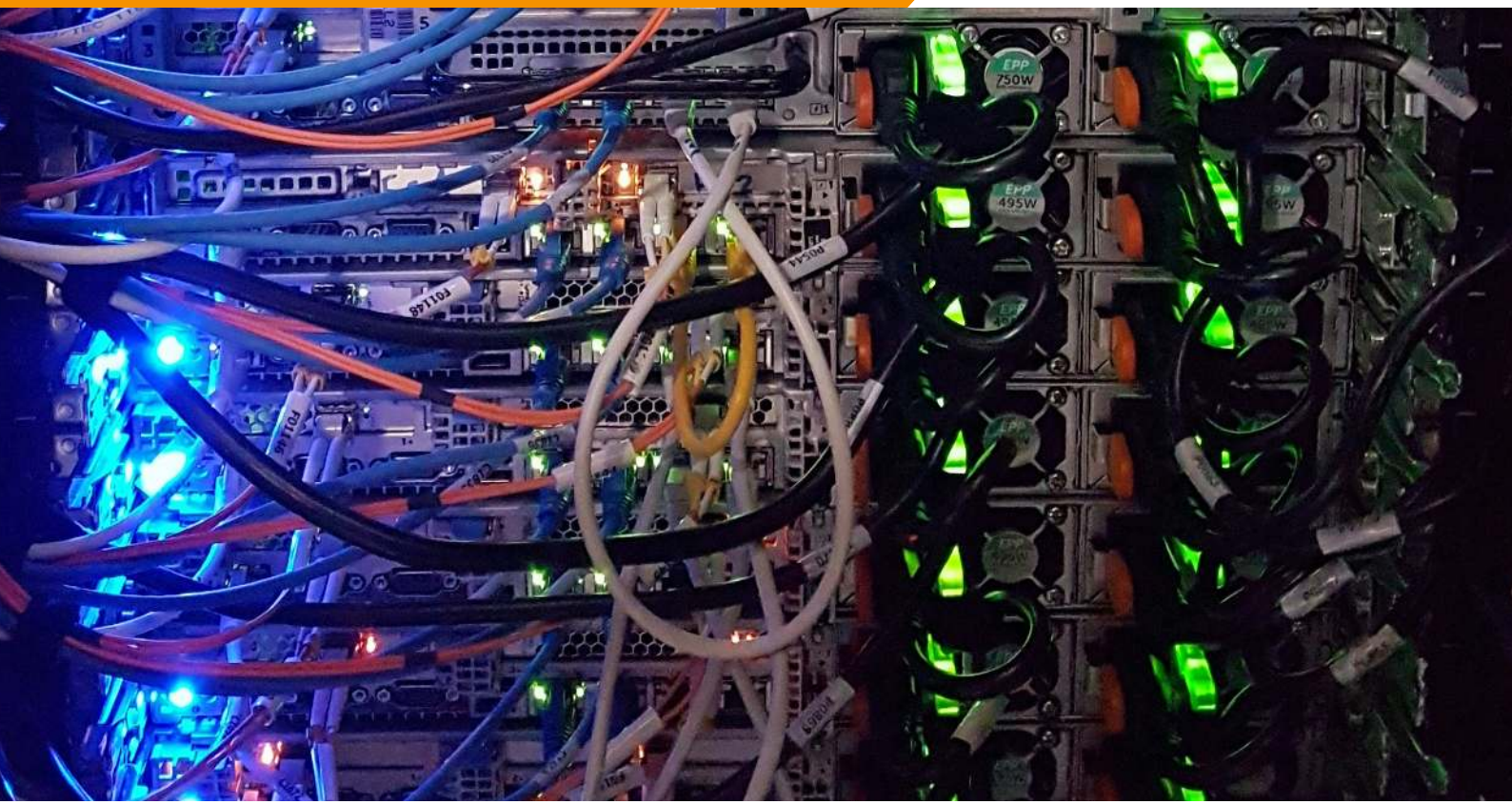


Realtime Communication — TSN, DetNet and OPC UA

Industrial real-time systems require both real-time computing and real-time communication. While Linux provides real-time computing through Preempt-RT, real-time communication is supported via Time-Sensitive Networking (TSN). This can be complemented by OPC UA — and in particular OPC UA FX — providing a standardized communication protocol for industrial use cases capable of replacing proprietary fieldbus technologies. Additionally, with Deterministic Networking (DetNet), more complex Layer 3 networks can be realized, enabling scalable edge and cloud applications. Together, TSN, OPC UA FX, and DetNet provide the foundation for a fully open and interoperable real-time communication stack.



In industrial automation numerous different field bus technologies like EtherCAT or Profibus are utilized to connect operational equipment. Sensors, actuators, and controllers commonly rely on diverse communication protocols, many of which are incompatible with one another or use proprietary standards. While Ethernet has already replaced a zoo of data link layer protocols for telecom and enterprise networks decades ago, its wide-spread application on industrial field level was hindered by the lack of real-time guarantees. This changed with the standardization of Time Sensitive Networking (TSN) in the IEEE, introducing guaranteed latency bounds, zero packet loss, and time synchronization into the Ethernet standard that are on-par with or even exceeding the capabilities of conventional field bus technologies.

However, TSN only standardizes the data link layer (layer 2), so for a full communication stack it depends on upper layer protocols. This could be, for example, PROFINET over TSN providing an easy transition from conventional PROFINET networks, but for a fully interoperable solution, OPC UA is the protocol of choice.

Already supporting TSN with OPC UA PubSub for quite some time now, the OPC UA Foundation has initiated the Field Level Communications Initiative to develop OPC UA FX, for a feature-complete field level communication solution based on TSN.

With TSN and OPC UA FX, a comprehensive solution for real-time communication on the factory floor is available. At the same time, this stack paves the way for even larger or more complex networks to support edge computing scenarios. This is where Deterministic Networking (DetNet), standardized by the IETF, comes into play, being able to route real-time traffic between multiple layer 2 networks, providing network segregation for increased security and performance.

Time-Sensitive Networking with Linux

The mainline Linux kernel has evolved into a robust platform for TSN applications, with comprehensive support for relevant IEEE standards that enable predictable, low-latency networking essential for industrial automation or professional audio applications.

For example, the kernel implements the standardized Enhancements for Scheduled Traffic (formerly known as IEEE 802.1Qbv or Time-Aware Shaper) through the TAPRIO qdisc, to provide time-slotted communication via dedicated queues to prevent any disturbances from parallel traffic. The kernel together with the Linux PTP application also support the precision time protocol (PTP) for achieving highly accurate time synchronization.

To support real-time applications, the Linux kernel also comes with a variety of socket types. The conventional AF_INET socket is a convenient option to hide most of the complexity of the network stack from the application, but since the Linux network stack itself is mostly optimized for versatility and throughput instead of latency, it is not really suitable for real-time applications. With AF_PACKET, the application is responsible to fully construct the packet including headers, but can profit from lower latency by circumventing most parts of the Linux network stack. Finally, with the eXpress Data Path (XDP), the Linux kernel provides the ability for full zero-copy packet handling between network cards or network card and application.

Together with many further capabilities, the Linux ecosystem is the most feature-rich platform for implementing TSN applications with the additional advantage of being completely open source and supporting the majority of TSN-capable hardware such as the Intel i226 Ethernet controller. A further benefit of using Linux together with TSN is the ability to implement converged networks, where real-time applications run together with non-real-time applications via the same wire. For non-real-time applications, the full power and complexity of the Linux networking stack supporting an abundance of networking applications out-of-the-box, can be used, while the TSN capabilities ensure that these applications do not impact the real-time performance of latency-sensitive applications.

Linux RealTime Communication Testbench

To validate this behavior or to benchmark hardware, the open-source RTC-Testbench was developed: https://github.com/Linutronix/RTC-Testbench

The tool generates and checks simulated payloads, including PROFINET and OPC UA PubSub, and is highly configurable with regards to cycle time, frame size, socket types and traffic class mapping. It records achievable jitter and latency and can optionally display live measurements via a Grafana dashboard for demonstrations or long-term measurements. Linutronix is the maintainer and core contributor to the RTC-Testbench which was funded by Phoenix Contact, Siemens and Intel and has found wide-spread application from developing Ethernet controllers to validating industrial deployments.

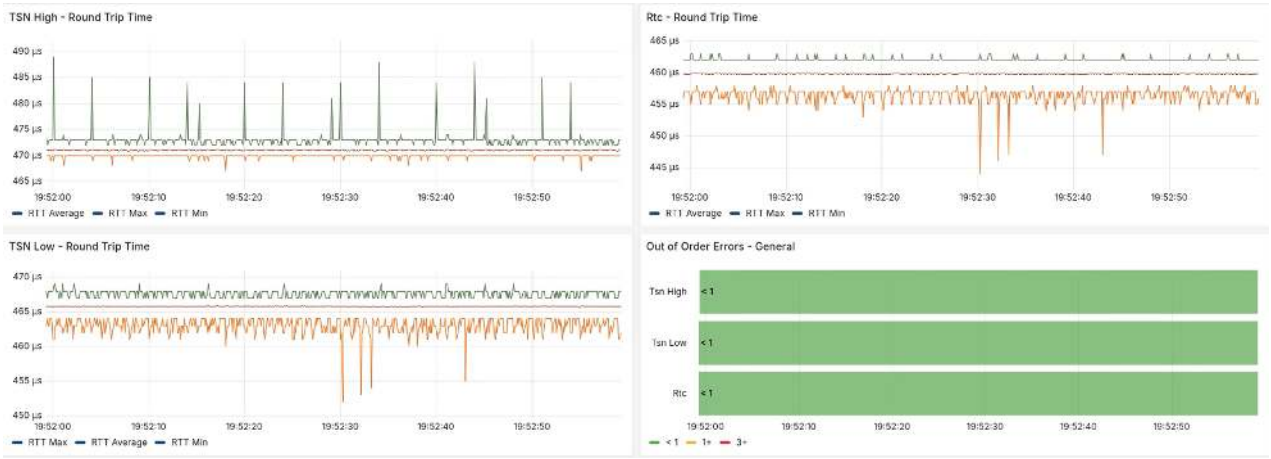


Figure 1: Measurements of the RTC-Testbench

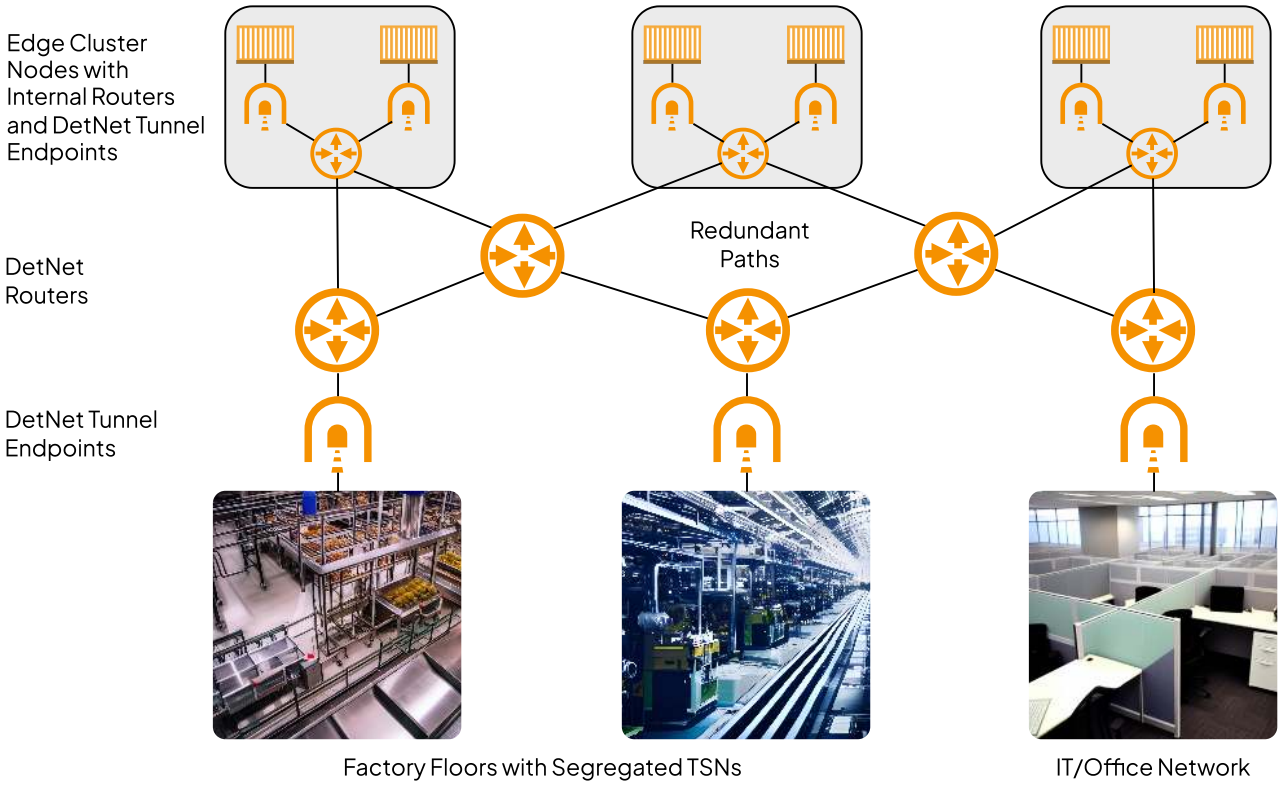


Figure 2: Converged DetNet Architecture with Edge Cloud

OPC UA with open62541

To provide a comprehensive communication stack on top of TSN, Linutronix is also involved in the development of open62541, an open-source implementation of the OPC UA standard. With contributions such as the Security Key Service (SKS) or the integration with Avahi for proper mDNS support, Linutronix addresses specific customer and research project requirements while at the same time delivering valuable features to the broader open62541 community. While open62541 already supports OPC UA PubSub and is already productively used in many TSN applications, further key features of OPC UA FX like the connection manager are still missing. If you are interested in using OPC UA (FX) for your application or advancing the OPC UA FX standardization, get in touch with us!

Deterministic Networking (DetNet)

While TSN works well for layer 2 networks in localized scenarios, such as a single factory floor or festival stage, it struggles to scale to more complex environments like industrial parks or whole broadcasting studios. Achieving fully deterministic end-to-end communication in these settings is impractical with TSN alone, limiting applications such as offloading real-time compute (e.g., image processing or AI tasks) to industrial data centers or flexibly routing low-latency audio between studios. This limitation arises because, without routing between segregated layer 2 networks, phenomena like broadcast storms can severely degrade performance, and ensuring security becomes difficult. Also further large networks like those operated by energy distribution companies or telecom providers rely heavily on layer 3 mechanisms.

This motivated the initiation of the IETF DetNet working group. Its goal is to standardize layer 3 networks providing techniques such as protection against packet loss and jitter due to contention, equipment failures and impacts of network topology changes to align with the communication requirements of industrial applications. DetNet can built up on a strong foundation provided by TSN and only needs to address certain details that are important when interconnecting several layer 2 TSNs. E.g., RFC 9023 is a quite short read and already covers the most important aspects of setting up a layer 3 network on top of TSN.

Figure 2 depicts how a DetNet could look like. The bottom shows several networks — either layer 2 (e.g., a TSN) or already layer 3. Each network is connected to a DetNet tunnel leveraging existing technologies such as IPv6 and MPLS PW to encapsulate the Ethernet packets while separating the different traffic flows. Thereby, the Ethernet packet, including its mapping to a specific VLAN, can be reconstructed at the egress tunnel endpoint. Furthermore, DetNet is able to replicate the traffic flows so that they can be routed over redundant paths in the network. By this, issues from faulty equipment or cables can be mitigated.

Linutronix is actively working on the vision to realize a real-time edge cluster. All relevant process data shall be sent to and from a central computing cluster. The flexibility and scalability both in terms of computing power as well as storage allows for many applications ranging from complex data analytics over advanced image processing to AI workloads.

DetNet allows applications running in the edge cloud to communicate with devices on the factory floor, while encapsulation enables communication over shared network infrastructure. It also enables independent management of different domains. E.g., VLAN IDs can be assigned independently because they will be mapped to distinct DetNet flows.

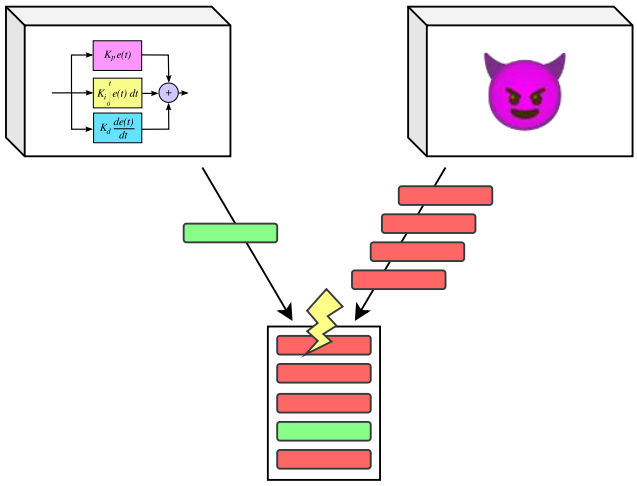


Figure 3: Clogging up a Network Queue with Illegitimate Traffic

detnetctl

But as with most new technologies, there is a catch: Network equipment manufacturers hesitate to invest until technology and demand is proven, but without devices in the market for exploration customer demand stays low. This is where Linux comes in. By leveraging existing features and contributing missing pieces, Linutronix has built both a DetNet router and a DetNet edge cluster node using off-the-shelf Intel hardware. This setup enables experimentation with DetNet capabilities and provides a foundation for real-world deployments.

To configure an industrial PC accordingly, the detnetctl tool was developed, available at https://github.com/Linutronix/detnetctl as open-source. It replaces cumbersome configuration tasks, e.g., TAPRIO qdisc setup, with convenient YAML or NETCONF/YANG configuration. The latter uses standardized data models to work seamlessly together with compatible networking equipment like switches.

For running multiple application containers on the same node, it is important to prevent hostile or inadvertent disturbances of the real-time behavior by parallel applications. Even the pure existence of additional network traffic in a real-time queue is problematic, leading to packet loss and extensive latencies (see Figure 3). With detnetctl all traffic is routed to independent queues while the application does not even need to be aware that its traffic will be transmitted with real-time guarantees.

Conclusion

With TSN, DetNet and OPC UA, a complete and modular real-time communication stack can be realized, based on open standards and open source software. With this architecture it is possible to build up true convergent networks carrying both conventional IT traffic such as web-browsing, mail or video telephony and at the same time critical OT traffic such as industrial sensing and control. It does not only allow to reuse the same infrastructure for reducing deployment and maintenance costs, but also enables to offload computing or storage intensive applications to edge data centers where cloud technologies such as virtualization or containerization can be applied.

With its expertise in real-time compute and real-time communication, Linutronix is at the forefront of technology and is regularly involved in research projects. Experts from Linutronix are active in standardization efforts and are invited to events of standardization working groups, e.g., the Avnu Alliance, IEEE, and IETF, to present how to realize emerging standards with Linux.

Besides heavily contributing to the Linux kernel, Linutronix is maintaining tooling such as the RTC-Testbench or detnetctl and contributes to open62541. With this, Linutronix supports its customers building up the industrial plants of the future with open-source software.

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