Network Slicing for Ultra-Reliable Low Latency Communication in Industry 4.0 Scenarios

Anders Ellersgaard Kalør, René Guillaume, Jimmy Jessen Nielsen, Andreas Mueller, and Petar Popovski

Abstract

An important novelty of 5G is its role in transforming the industrial production into Industry 4.0. Specifically, Ultra-Reliable Low Latency Communications (URLLC) will, in many cases, enable replacement of cables with wireless connections and bring freedom in designing and operating interconnected machines, robots, and devices. However, not all industrial links will be of URLLC type; e.g. some applications will require high data rates. Furthermore, these industrial networks will be highly heterogeneous, featuring various communication technologies. We consider network slicing as a mechanism to handle the diverse set of requirements to the network. We present methods for slicing deterministic and packet-switched industrial communication protocols at an abstraction level that is decoupled from the specific implementation of the underlying technologies. Finally, we show how network calculus can be used to assess the end-to-end properties of the network slices.

I. INTRODUCTION

Industry 4.0 refers to the fourth industrial revolution that transforms industrial manufacturing systems into cyber-physical systems by introducing modern and emerging information and communication technologies, such as 5G connectivity and cloud computing [1], [2]. Specifically, one of the generic services in 5G termed Ultra-Reliable Low Latency Communications (URLLC) is poised to bring wireless connections of unprecedented reliability, such as $1 \times 10^{-6}$ [3], [4]. This will give rise to new designs of machines and robots, released from the constraints imposed by cabled connections and the need for physical attachment. Nevertheless, not all connections will always require ultra-high reliability. In some use cases high data rate may be required and in others, simultaneous support of many connections is required. In fact, the connected industry will feature connections of all three types envisioned in 5G: enhanced Mobile Broadband (eMBB), massive Machine-Type Communications (mMTC) and URLLC [5].

Simultaneously satisfying diverse connectivity requirements within the same system is challenging since the network cannot be optimized for a specific type of service. A promising approach to handle this problem is network
slicing, which refers to the process of slicing a physical network into logical sub-networks which are each optimized for specific applications with certain characteristics \[6\]. For instance, as illustrated in Fig. 1 one network slice may offer URLLC based information access by reserving communication and buffer resources along a path from the end-user to an edge cache, or to a database in the cloud (network slice 1). At the same time, another network slice in the same physical network may offer an eMBB service between a robot and the Internet, e.g. to allow for firmware updates (network slice 2). Network slicing is enabled by recent network technologies such as Software-Defined Networking (SDN) and Network Function Virtualization (NFV) to decouple the network control plane from the data plane, and to centralize the management of routing, queues, etc.

A. Network Slicing for Industry 4.0

Although encompassing eMBB, mMTC, and URLLC, Industry 4.0 is characterized by its very strict latency and reliability requirements. For instance, control systems and alarm systems may require a delivery reliability in the order of $1 - 10^{-9}$ and end-to-end latencies in the range of 0.5–5 ms [4]. As a result, network slicing for industrial networks poses several challenges. First, constructing network slices with strict end-to-end latency and reliability guarantees as required by industrial applications is challenging due to the difficulties in modeling and predicting queuing delays with high accuracy. Secondly, industrial networks are often very heterogeneous, comprising many specialized legacy protocols, which complicates accurate end-to-end analysis [7]. Guaranteeing low latency and high reliability has traditionally been accomplished through the use of determinism and cyclic communication with reserved resources and limited options for dynamic configuration. This configuration is not ideal for Industry 4.0 where low latency traffic not only may have to pass several links to reach the cloud, but also is highly dynamic due to the high mobility introduced by wireless technologies. Instead, technologies with mechanisms for low-latency communications may be more favourable, such as URLLC and Ethernet TSN which has received much attention.
in the communities for industrial communication [8]. However, it is unlikely that all protocols will be replaced by new technologies at once, and network slices need to work across both new and existing technologies. Therefore, network slicing must be studied and resolved at an abstraction level which captures the main characteristics of the protocols but is decoupled from the specific implementations, such as legacy protocols, URLLC and Ethernet TSN.

In this article, we present methods for slicing industrial communication protocols with focus on applications which require strong reliability and latency guarantees analogous to those targeted by URLLC. To this end, we investigate the utilization, reliability and isolation trade-offs of the methods in an abstract setting which is independent of the specific details of the protocols, and we demonstrate how end-to-end properties of the proposed network slicing methods can be calculated across communication technologies using network calculus, both for a specific use case and in a general setting. The remainder of the article is organized as follows. Section II introduces methods for slicing industrial networks. Section III describes a personalized medicine manufacturing system, which is used to illustrate how end-to-end delivery reliability and latency bounds can be obtained. Finally, the article is concluded in Section IV.

II. NETWORK Slicing METHODS

Industrial networks commonly follow a hierarchical structure as illustrated in Fig. I. The individual devices such as actuators, sensors, etc. are connected in a factory unit, and are typically controlled by a master device in a master/slave configuration. The connection may be wired or wireless, or in a combination where a small 5G base station is part of the factory unit, e.g. if there is need for high synchronization between the devices. The factory unit is usually based on a deterministic and cyclic protocol, with resources reserved to the individual devices in each cycle. The cycle times may vary from sub-millisecond to several milliseconds depending on the system. The master devices of the individual factory units are connected to a factory-wide network, which may also be connected to an external infrastructure such as the Internet. The factory network is typically based on switched protocols such as regular Ethernet or Ethernet TSN and possibly TCP/IP. It includes general purpose hardware and cloud computing resources which can be used by the master devices, or even by components in a factory unit, and may comprise one or more 5G base stations, which provide wireless connectivity to devices in the factory.

We now describe slicing methods for cyclic protocols within factory units, followed by a discussion and analysis of network slicing in switched networks at the factory-wide network.

A. Factory Units

As a factory unit, we consider a single master/slave network with a fixed cycle time. Each cycle contains a number of resources (bytes), which are each allocated to a specific application running on a certain device. The allocation is fixed and cannot change during operation. We consider a network comprising one deterministic application which transmits in every cycle (e.g. sensor readings for closed-loop control), and $K$ stochastic applications which transmit frames randomly (e.g. sensor alarms). The deterministic application transmits $R_d$ frames of size $N_d$ in every cycle, while the number of frames transmitted by stochastic application $k$ is denoted by $R_k$, and of fixed size $N_k$. 
An obvious slicing scheme is to simply assign a number of resources in each cycle to the individual applications based on the amount of data that they transmit (Fig. 2a). Suppose we allocate $N_k'$ bytes to stochastic application $k$. Neglecting transmission and other error sources, and assuming that excess frames are not buffered but dropped, the reliability of the scheme is simply the probability that all arriving frames can be transmitted, $Pr(R_k N_k \leq N_k')$. Furthermore, assuming that $N_d' = R_d N_d$ bytes are allocated to the deterministic application, it cannot fail due to resource shortage. The proposed scheme provides a high degree of isolation between applications and is simple to analyze, but it results in a low resource utilization if data is not transmitted in every cycle. This is particularly prominent for bursty transmissions with high reliability requirements. Although the utilization could be improved by introducing queuing to the system, this complicates the analysis, in particular when the arrival distribution take a more complex form, which makes it difficult to provide end-to-end guarantees.

An alternative slicing scheme is where resources are allowed to be shared between the $K$ stochastic applications. This results in an increased statistical multiplexing gain due to the increased aggregate arrivals, and hence an improved resource utilization. Under this scheme, an allocation of $N'$ bytes are shared between $K$ applications, so that it fails when the aggregate arrival exceeds $N'$, i.e. $\sum_k R_k N_k > N'$. However, although the scheme increases the utilization, the gain comes at the cost of reduced isolation due to multiplexing between the applications. Specifically, the transmissions by one application influence whether other applications can transmit. This may in particular be problematic when there are uncertainties in traffic models, due to its impact on the system reliability. Furthermore, without introducing scheduling mechanisms, the scheme cannot take diverse reliability requirements into account, e.g. through application prioritizing. Therefore, it is most useful when multiple applications transmit the same type of data, such as sensor readings.

Although multiplexing increases the utilization for high aggregate arrival rates, it still achieves a low utilization for apps with low arrival rates with high reliability requirements. To improve the utilization for rare transmissions, we consider a scheme where high-priority applications are allowed to overwrite specific resources allocated to other applications (Fig. 2b). This is also referred to as puncturing in the context of 5G. For instance, a closed-loop control system may obtain feedback from a sensor in each cycle, but remain stable during short interruptions of the feedback loop. Hence, the system provides a higher reliability than needed. Suppose that each frame transmitted...
by a stochastic application overwrites a random (uniformly distributed) frame from the deterministic application. We assume that two application frames cannot overwrite the same periodic frame, even if the sum of frame sizes is smaller than the size of the periodic frame. The reliability of the deterministic traffic is the probability that a frame allocated to the deterministic application is not overwritten by any of the application frames, while a stochastic application transmission fails if the aggregate arrival $\sum_k R_k$ exceeds $R_d$.

B. Factory-Wide Networks

The factory-wide network is based on packet-switched technologies where frames are queued at each link to increase the link utilization. However, queuing introduces a random delay which depends on the traffic that shares the link. In simple networks, the frames may be processed as first-in-first-out, while complex networks may apply various queue schedulers to control the flow and prioritize certain types of traffic. A precondition for using switched networks in Industry 4.0 is the ability to analyze the queuing delay of the traffic with strict end-to-end latency requirements. Several methods for queuing delay analysis exist, including queuing theoretic approaches [9] and stochastic network calculus (SNC) [10], which give probabilistic results about the queuing delay, and deterministic network calculus (DNC) [11] which provides worst-case latency bounds. While the probabilistic results from queuing theory and SNC allow for exploiting the system requirements more efficiently than DNC, the traffic arrival and server models are often strongly restricted in order to keep the analysis tractable, which limits the usefulness of the methods. In particular, they are not well suited for industrial networks where the traffic is generated by a mixture of periodic and stochastic sources, and where the network requirements are too strict to allow for model approximations and uncertainties. On the contrary, DNC allows for analyzing worst-case latencies as long as the arrival processes are bounded by some function. Since the network within a factory units has finite resources per cycle, this provides a bound on the arrival processes. Therefore, we focus on modeling the latency using DNC, although the other methods could be applicable in some scenarios as well. We omit a detailed presentation of DNC here, and instead refer to [11], [12] for a thorough treatment.

The theory of DNC is based on the notion of arrival and service curves which are functions that bound the cumulative number of bytes arriving to and being served by a queue. Although the theory of DNC is very general and results can be obtained with many types of curves, the curves are often restricted to affine bounds to simplify the analysis. For example, the arrivals from an application that generates a frame of size $N$ periodically every $M$ time units would be bounded by the affine function $A(t) = [N/Mt + N]_+$ where $[x]_+ = \max(0, x)$. Similarly, the service rate of a server, modeling the serialization of frames, may be lower bounded by the affine service function. Several results can be obtained from DNC, as exemplified in Fig. 3. Here, $A(t)$ defines the affine bound on traffic 32 bytes arriving periodically in every cycle of duration $t$, and $S(t)$ is the service curve defining the rate at which the arriving bytes are served. From $A(t)$ and $S(t)$, one may obtain the waiting time bound $W(t)$ and the departures from the queue, $D(t)$, which may in turn be used as arrival curve to the next queue in the path for end-to-end analysis. Furthermore, through the notion of leftover service, DNC allows for analyzing multiple queues with various scheduling policies such as prioritization queuing. Leftover service refers to the minimum service that is available to a queue after other queues have been served. This is important in the context of industrial applications,
where scheduling, and in particular traffic prioritization, is necessary to guarantee low end-to-end latencies with high probability. Other quantities that can be obtained from DNC include maximum queue size which can be used to dimension buffers.

### III. CASE STUDY: PERSONALIZED MEDICINE MANUFACTURING

This section introduces a simple personalized medicine manufacturing system as a use case of Industry 4.0 to demonstrate how network slicing can be used to handle diverse end-to-end network requirements. Furthermore, the system will be used to study the trade-offs in the slicing methods presented in previous section. The system is derived to contain the main properties and realistic requirements of an Industry 4.0 system, and is based on the potential URLLC requirements defined by 3GPP [3]. It is described in an abstract way, which is independent of the specific communication technologies used in the network, so that it can represent both wired legacy protocols and URLLC technologies.
The system consists of 10 identical master/slave factory units connected using an industrial cyclic communication protocol. The master devices of each factory unit are physically located at the base station, and connected to a cloud through a hierarchical switched factory-wide network as depicted in Fig. 4. Each of the 10 factory units controls a pipetting machine mounted on a robotic arm, which dispenses a drug product into a container. The type and amount of drug is determined based on patient information obtained from a patient database in the cloud. To validate the process the final product is weighed after the drug has been dispensed, and the weight is stored in the cloud. Finally, the entire process can be monitored by an operator using an Human Machine Interface (HMI) which is connected to the factory unit, and displays a video streamed from the cloud. Furthermore, a number of sensors are located in the unit to supervise the process, which may raise alarms in case of failures. The requirements to the network are listed in Table 1.

The factory unit networks are based on a master/slave communication protocol with a cycle time of 1 ms. The factory-wide network is based on switched 100 Mbit Ethernet, and the switches are equipped with prioritization queues to each outgoing link. To simplify the setting, we assume that each link only has two queues. Furthermore, since we are mainly interested in the trade-offs in using various slicing schemes, we consider a unified channel model where the frame delivery reliability of the links in both the factory units and the factory-wide network is $1 - 10^{-9}$.

A. End-to-End QoS Analysis

There are numerous combinations of the network slicing schemes from Section II that may satisfy the application requirements in the medicine manufacturing system, and a complete treatment is beyond the scope of this article. Instead, we focus on a few applications and illustrate how the proposed slicing schemes and DNC can be used to obtain end-to-end results of the individual network slices, as well as to analyze the interaction between the slices. For simplicity, we ignore propagation delays and focus on queuing. Furthermore, we ignore potential overhead added by protocol headers in the network, and use milliseconds as the time unit.
We first consider the resources for the sensor alarms. Since the number of alarms in each cycle is random, we can either reserve a fixed number of resources in each cycle, or we can allow alarms to overwrite the cyclic control traffic, which has a lower reliability requirement. Allocating a fixed number of resources results in a low utilization, while overwriting control traffic introduces a decrease in the reliability of the control traffic. Since the rate of alarms is very low compared to the cycle time, the overwriting scheme is a promising approach for this use case. Figure 5 shows the end-to-end frame failure probabilities of the alarm and control traffic for a mean number of alarm arrivals per cycle, $\lambda$. We consider the cases where the control traffic comprises 1 and 4 frames, $R_{\text{control}} = 1 \cdot 128$ and $R_{\text{control}} = 4 \cdot 32$. At a low number of arrivals, the reliability approaches the reliability of the links. Since there is only a single link between the source and destination of the control traffic, compared to three links for the alarms, its reliability is significantly higher. As the number of arrivals increases, the reliability decreases for both the control traffic and the alarms. The decrease in the control traffic reliability is due to a higher probability of being overwritten by an alarm, while the decrease in alarm reliability is due to an increased probability of experiencing a shortage of resources in a cycle. In the specific use case considered in this article, the reliability requirement of the control traffic is $1 - 10^{-6}$, which can be achieved up to an arrival rate of $\lambda = 4 \cdot 10^{-6}$ for $R_{\text{control}} = 4 \cdot 32$. Consequently, this is sufficient for the expected inter-arrival time of 60 s ($\lambda \approx 1.7 \cdot 10^{-4}$), and hence the overwriting slicing scheme would be a reasonable choice. Furthermore, the reliability of the alarm traffic at this point is very high since it is unlikely that two alarms arrive in the same cycle, and since the resources are used in all cycles, the utilization is 100 percent. By comparison, if 32 bytes were allocated in each cycle only to the sensor alarms, it would on average only be used once every 60 seconds, yielding a utilization of approximately 0.02 percent, and would in addition occupy 32 bytes more of the frame than the overwriting scheme.

A consequence of the prioritization queuing scheme in the factory network is that the isolation between the queues is limited, since an increase in the high-priority traffic also results in an increased queuing delay of the traffic of lower priority. Suppose now that we in the factory units decide to use the overwriting scheme for the alarm traffic. Furthermore, assume that we give sensor alarms high queue priority in the entire path from source to destination, and that the periodic patient info requests are given second priority. Obviously, the queuing delay that the patient info requests experience depends on the number of sensor alarms. The maximum number of bytes that can arrive to the factory network from the alarms is enforced by the number of control frames that can be overwritten. Specifically, in the cases considered above where 1 or 4 control frames are allocated, at most 1 or 4 alarm frames can arrive to the factory network in each cycle (1 ms). Using this bound, we may use DNC to obtain a bound on the total end-to-end latency experienced by both the alarm frames and the patient info requests. This is illustrated in Fig. 6 for various sensor alarm arrival bounds, $R_{\text{alarms}}$. As $R_{\text{alarms}}$ approaches 0, the alarm latency approaches the cycle time of 1 ms. For increasing $R_{\text{alarms}}$, the latency experienced by both the sensor alarms and the patient info requests increases due to an increased serialization time. Notice that despite being unchanged, the patient info request latency increases with a larger slope than that of the sensor alarms. This reflects the conservatism of the affine bound, and is due to accumulation of low-priority frames in the time where the high-priority traffic is served. In a system with more queuing priorities, the accumulation would occur at each prioritization queue all the way to the queue with lowest priority. Although the latency is still low in the shown scenario, it shows that
Fig. 5: End-to-end failure rate of control and sensor alarm traffic in the network slicing scheme based on overwriting for various alarm arrival rates.

Fig. 6: End-to-end latency of sensor alarms and patient info requests for various alarm arrival rates.
enforcing a limit on the number of bytes entering the factory-wide network is important to maintain the required latency. This can either be done by exploiting the reserved resources in the factory units as done here, or by inserting traffic shapers, such as token buckets, into the network.

IV. CONCLUSION

5G, and particularly URLLC, will play an important role in transforming industrial manufacturing systems into Industry 4.0. Furthermore, a wide range of new applications will emerge due to the increased connectivity, and they will have a diverse set of requirements to the network, ranging from ultra low-latency cyclic delivery guarantees to best-effort and high data rates. This article investigates network slicing as a way to handle this diverse set of application requirements, with focus on URLLC. We have presented methods for slicing both cyclic and switched industrial protocols at an abstract level, and discussed their trade-offs in utilization, reliability and isolation. Furthermore, using a case study of an industrial medicine manufacturing system with diverse network requirements, we have illustrated how deterministic network calculus can be used for analyzing end-to-end latencies of network slices comprising both deterministic and switched networks.

ACKNOWLEDGMENT

The work by J. J. Nielsen and P. Popovski has partly been supported by the European Research Council (ERC Consolidator Grant nr. 648382 WILLOW), and partly performed in the framework of the Horizon 2020 project ONE5G (ICT-760809) receiving funds from the European Union. The work by R. Guillaume and A. Mueller is supported by the Federal Ministry for Education and Research (BMBF) within the project Future Industrial Network Architecture (FIND) (16KIS0571).

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