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Enhancing Reliability by Combining Manufacturing Processes and Private 5G Networks

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***Abstract*—The ongoing process of shop floor digitalization makes production processes more transparent and helps technical staff and managers at their day-to-day work in modern factories. The digitalization is enabled by a wide variety of applications which run on different device types and demand support for different network characteristics.**

Providing a 5G campus network that satisfies all of the different network requirements at all times is not economically reasonable. Instead, the network softwarization functionalities of 5G should be used to configure the mobile network to specifically support certain applications at certain times. A network configuration targeted towards specific applications makes the best possible use of limited network resources.

In this paper we present an architecture that links manufacturing processes to a 5G campus network in order to apply a network configuration targeted towards the manufacturing applications in the next production schedule. Furthermore, our architecture comprises network stress tests to ensure that the network configuration works as expected.

***Index Terms*—5G campus network, MES, STING**

I. INTRODUCTION

Over the last few years, computer networks became a very hot topic for machine park operators and manufacturers as a necessary part of the shop floor digitalization. Machines are monitored and controlled by a supervisory control and data acquisition (SCADA) system and a manufacturing execution system (MES) which schedules production orders in conjunction with the enterprise resource planning (ERP) system. Smartphones, tablets and smart glasses assist machine operators, maintainers and managers on the shop floor. Industrial Internet of Things (IIoT) devices generate further data to enrich data collections which can be analyzed for predictive maintenance and predictive quality. All in all, there are heterogeneous applications with manifold protocols on the shop floor.

For machine park operators like Weidmüller, shop floor digitalization brings not only opportunites, but also challenges. Weidmüller is a manufacturer for factories around the globe, offering a variety of different products ranging from electrical terminal blocks to complex automation solutions. Currently, most of the factory network traffic is transmitted via cable-based Ethernet networks. Wi-Fi enables selected mobile applications. However, the limitations of these technologies are apparent [1]. Cable-based networks are not appropriate for mobile devices and Wi-Fi runs into scalability problems for a large number of devices. 5G can offer improved network service quality by providing higher data rates and lower latency for mobile applications. In addition, indoor positioning capabilities offer further potential for factories which is also of great interest for manufacturers. Therefore, 5G moves into the focus of manufacturers. Many industrial 5G use cases are already described by Wollschlaeger *et al.* [2] and Rao *et al.* [3].

However, 5G brings new challenges for manufacturers when it comes to the selection, dimensioning, operation and maintenance of 5G campus networks. The network load in a factory can vary. Machines are regularly moved on the shop floor due to lean-driven optimizations, and an increasing number of (possibly AR/VR-enabled) mobile devices stream spontaneously time-critical content parallel to the ever-present operational communication. Hence, a static network configuration may not meet all upcoming requirements in the best possible way. A flexible, on demand (re-)configurable network is desirable for balancing available network resources instead of oversizing the network.

In this paper, we present a concept to achieve such network (re-)configurations. We consider different manufacturing applications each of which having specific network requirements. We want to monitor the network traffic, adjust the network if it becomes necessary, identify critical scenarios and prevent congestion situations in advance (see Fig. 1). Therefore, production processes and the 5G network need to be connected in a way that the production planning systems can treat network capabilities as operating resources and perform demand-driven network configuation decisions. This enables both new innovative use cases as well as increased flexibility in existing applications after a 5G retrofit.

After this introduction we elaborate the idea of combining manufacturing processes and communication networks in Section II. In the main section Section III we present our approach and describe the corresponding system model architecture that shows the important systems, their relevant components and kinds of data they exchange. Section IV provides details about the interaction sequences between the different components in our architecture. Finally, we conclude our paper in Section V and give an outlook on future work.

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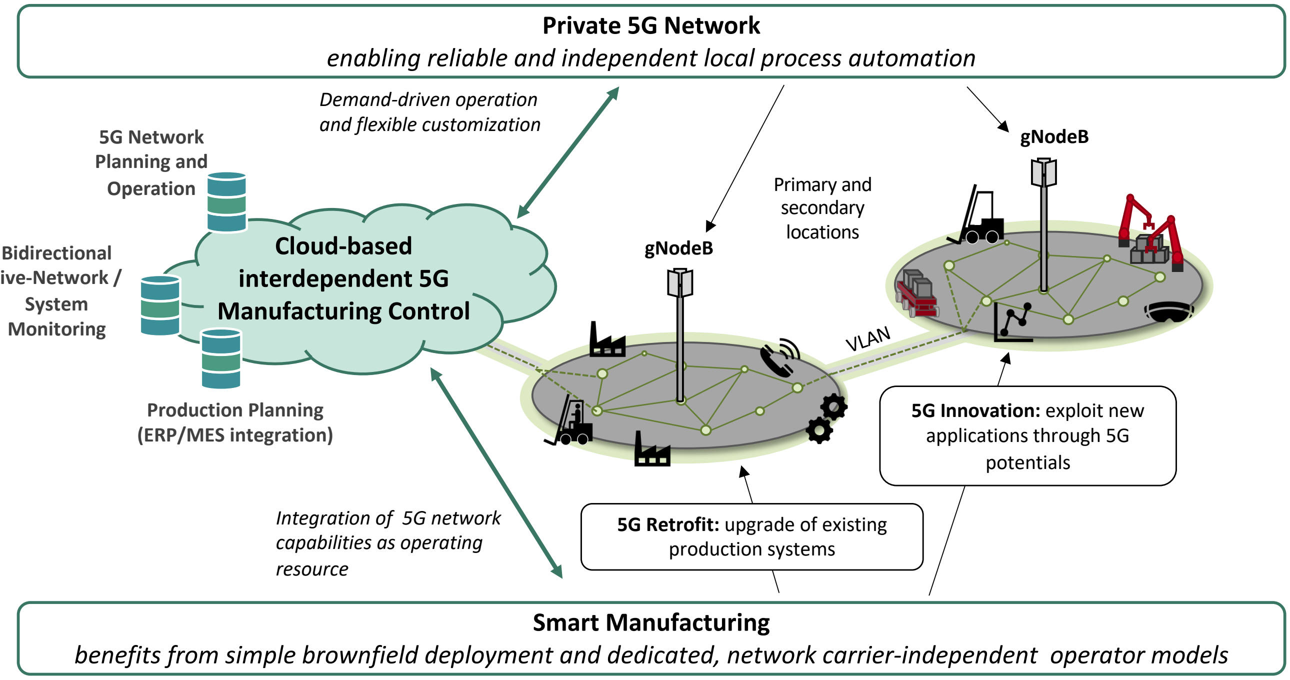


Fig. 1. Acclerating future manufacturing by mutual interaction with private 5G networks.

II. COMBINING MANUFACTURING PROCESSES AND COMMUNICATION NETWORKS

A. *State of the art*

Private 5G networks show a great potential for enabling new industrial use cases as well as providing a flexibility gain for existing applications, as described in [4]. First performance studies of private 5G networks have been conducted and depict promising results for industrial applications [5] [6]. Both studies indicate that 5G is able to provide a huge potential for future manufacturing processes, but also needs to be evaluated with respect to its desired use cases in order to guarantee a reliable network performance.

Traditionally an industrial network's configuration is fixed and static during productive operation. This also holds for modern industrial 5G network architectures like [7] or [8].

A 5G network on its own is oblivious to manufacturing processes, but provides network softwarization and virtualization tools which enable a flexible network configuration specifically geared to support certain applications [9]. Technologies such as software defined networking (SDN) and network function virtualization (NFV) permit network participants to dynamically and automatically adjust the network settings. Hence, in 5G networks participants cannot only interact *via* the network but also *with* the network.

As described in [10], a manufacturing execution system (MES) is a tool that supports planning and controlling manufacturing processes and ensures process transparency. Typical tasks are order, equipment, material and personnel management. Thus, the MES has domain knowledge about manufacturing processes, but it is oblivious of the communication network which it uses.

One can make use of the 5G network softwarization features to configure the communication network depending on the manufacturing processes which are planned in the MES. Then, the network resources can be provided on demand, based on business process knowledge and triggered by the MES. For this purpose, the business process logic controller (BPLC) concept was introduced in [11] for enabling business process-aware network optimization. That work argues that requirements which are derived from business needs can be dynamically transformed into network configuration changes. For example, the MES planned a machine maintenance session with remote support via augmented reality (AR) glasses. Then the MES can temporarily reserve network resources so that the video conferencing traffic from the AR glasses are processed with low latency and low jitter to ensure a good quality of experience. However, the BPLC's transformation from business requirements to network configurations does not consider physical limitations of the network and implicitly assumes that the network is powerful enough to always meet the business needs. Network stress tests were not addressed in [11]. An approach for testing NFV deployments is presented in [12] but these tests are focused on network services only.

B. *Our contribution*

We want to improve upon the BPLC approach by adjusting the manufacturing processes if the network is not able to fully meet the requirements of all desired manufacturing applications. Therefore this paper introduces a new system: the Manufacturing-Network Mediator (MNM). Apart from

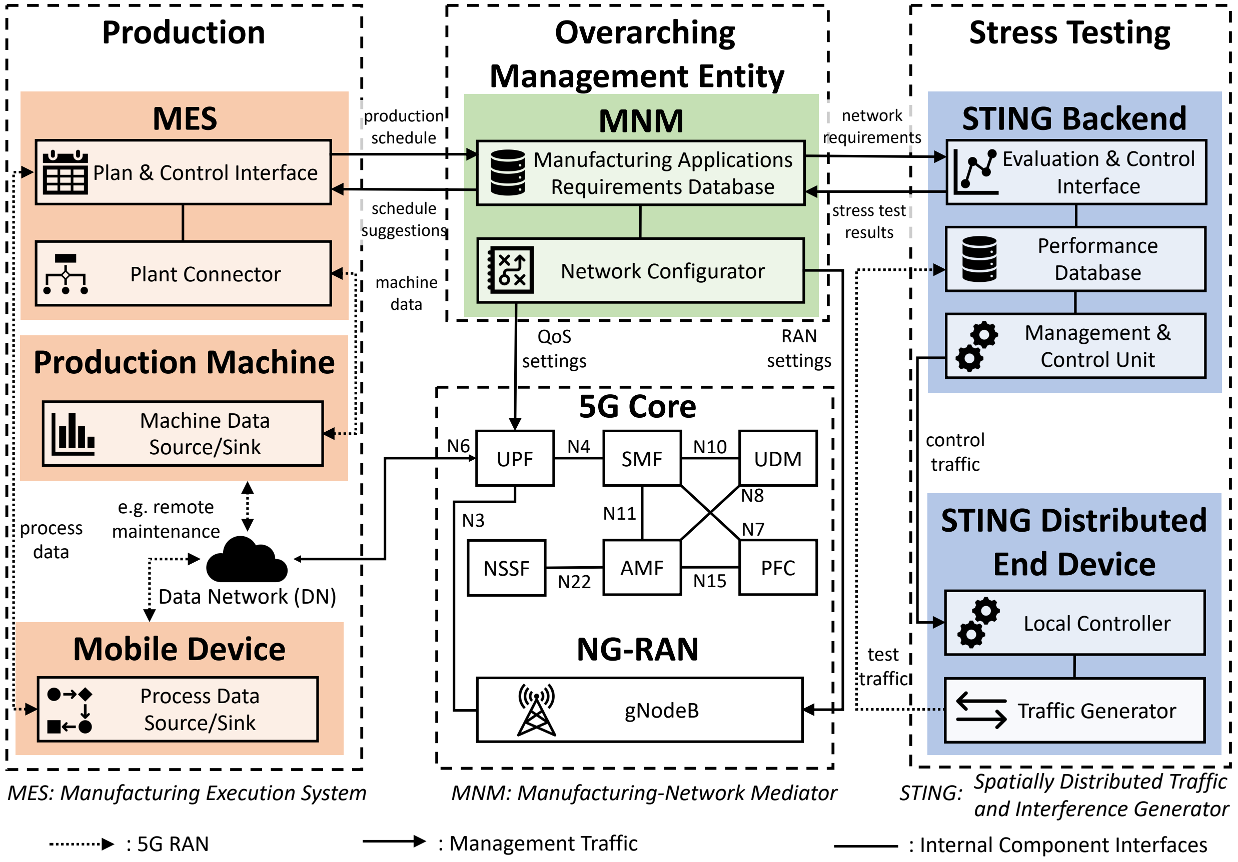


Fig. 2. The system model architecture of our approach shows the important systems and their relevant components as well as the kinds of data they exchange. Arrows indicate a data exchange. For dotted arrows the data exchange is performed via the 5G mobile network. Manufacturing-related systems are colored in red. STING systems are colored in blue. The MNM is colored in green.

the BPLC functionality, the MNM provides the MES with information about the real performance the 5G network can provide. To achieve this, we show how the Spatially distributed Traffic and Interference Generator (STING) [13] can be used by the MNM. After important changes of manufacturing processes, applications or devices, the MNM uses the STING to evaluate the network infrastructure with stress tests while recognizing position-dependent radio disturbances. The MNM reports the stress test results back to the MES, where manufacturing processes might be adjusted in order to avoid network congestions. Section III describes the basic architecture of our approach in detail.

III. SYSTEM MODEL ARCHITECTURE

Our system model architecture is depicted in Fig. 2. The following subsections give more details about its different components.

A. *Manufacturing-related systems*

Enterprise resource planning (ERP) systems manage business activities and support production planning for the whole company. In this paper we consider production planning for single production sites or production areas which is performed by a manufacturing execution system (MES). The production planner uses a Plan & Control Interface provided by the MES to create a detailed production schedule. During manufacturing the machine setters and operators exchange process data with the MES. The employees receive tasks from the Plan & Control Interface according to the production schedule and provide acknowledgments for completed tasks back to the Plan & Control Interface. With a mobile network available on the shop floor, employees can use mobile devices for these data exchanges with the MES. This reduces the distances they need to walk to stationary computers.

While trying to maximize the production output, the production schedule must respect limited resources, i.e. available machines, materials and personnel. In our approach the communication network is considered as a limited resource as well. For this reason the Plan & Control Interface is connected to the Manufacturing-Network Mediator (MNM) in our architecture. The MNM is described below in Section III-D. More details on the interaction between the MES and the MNM are given in Section IV.

Production machines on the shop floor are connected to the MES via a Plant Connector, which aggregates data directly from machines or from an intermediary middleware solution, which is an adapter supporting different industrial protocols such as OPC UA or Modbus/TCP.

Industrial protocol traffic can be characterized as periodically *polling traffic* (e.g. Modbus/TCP) and as *publish-subcribe traffic* (e.g. OPC UA). Especially the former traffic requires high network reliability since a reliable delivery in not guaranteed by the industrial protocol. There are also other forms of traffic for different manufacturing applications which communicate with internal or external servers in the Data Network (DN). For example the bulk transmission of backups or updates leads to *burst traffic* where a high data transmission rate is desirable. Another example is an application used for remote maintenance purposes. A remote maintenance application can be a video call application on a mobile device or a remote control tool, like TeamViewer or Windows Remote Desktop, on a machine computer. Remote maintenance applications rely on *time-critical stream traffic* and require low jitter and low latency.

B. The Spatially distributed Traffic and Interference Generator (STING)

The Spatially distributed Traffic and Interference Generator (STING) [13], as shown in Fig. 3, will be used to stress test the 5G network with the configuration which was derived by the MNM as described below in Section IV.

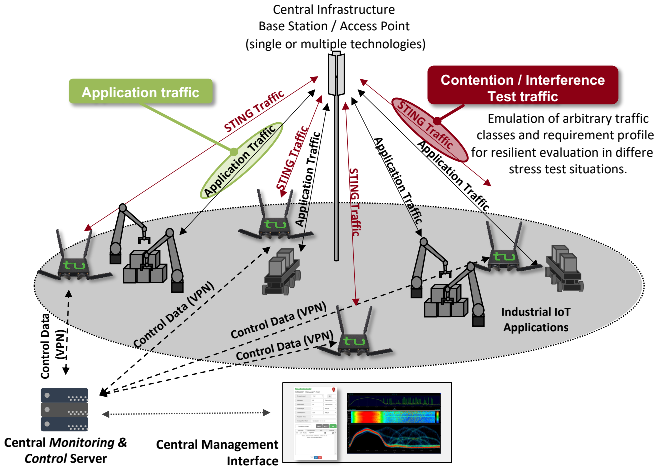
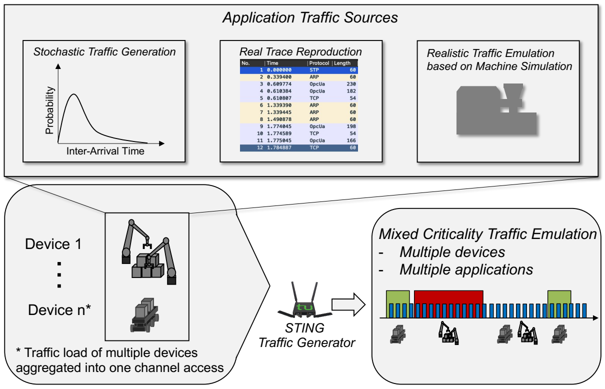


Fig. 3. Overview of the Spatially distributed Traffic and Interference Generator (STING).

STING can emulate real-world application traffic using independently located end devices within the network area in order to stress the network under test. The measurements obtained in this stress situation enable proper decision making about whether the targeted use cases can be achieved with a given network configuration even under heavy load. Each end device can act as a single or multiple real-world applications. The traffic generation process is modular, which allows different types of traffic processes sequentially or in parallel.

Streaming data traffic is emulated using the open-source traffic generator iPerf, while stochastic data transmissions are generated randomly based on their underlying distributions. To recreate real applications' traffic, it is possible to use a prerecorded packet capture file as a basis for a) stochastic traffic with the same characteristics, or b) replay the exact packet trace (see Fig. 4).

Another option for emulating data traffic is a machine simulator, which can generate realistic application traffic by simulating the actual machine functionality such as the Injection Molding Machine Simulator (IMMS) mentioned in [14].



No.	Time	Protocol	Length
1	0.000000	STP	60
2	0.339400	ARP	60
3	0.609774	OpcUa	230
4	0.610384	OpcUa	182
5	0.610807	TCP	54
6	1.339390	ARP	60
7	1.339445	ARP	60
8	1.490878	ARP	60
9	1.774045	OpcUa	198
10	1.774589	TCP	54
11	1.775045	OpcUa	166
12	1.784887	TCP	60

Fig. 4. Traffic Modelling Concept of STING.

Thus, there are ways to emulate the traffic patterns of manufacturing applications as planned by the MES. During the stress tests the STING tracks several performance metrics such as throughput, latency and packet error rate and stores them over time. These metrics are then populated back to the MNM as results in order to decide whether the planned manufacturing applications will work as expected with the current network configuration or not. If not, the network should be reconfigured or the production schedule should be adjusted.

C. 5G network functions required for quality of service

In Fig. 2, the 5G core network functions are included which are required to implement quality of service (QoS) settings. Other essential network functions are not shown, but a detailed description can be found in [15]. In the following, the relevant 5G elements of Fig. 2 are listed and described briefly:

- **User Plane Function (UPF)**: Potential user plane applications are implemented in 5G as so-called UPFs, which are provided directly in the 5G core network. This has potential gains in terms of latency reduction as user traffic is not required to be routed through the 5G core network into the Internet or other wide area networks (WANs). This also shows the increasing adoption of cloud concepts in 5G networks and also enables future technologies such as mobile edge computing.
- **Session Management Function (SMF)**: The SMF manages different sessions regarding UPFs.
- **Unified Data Management (UDM)**: The UDM acts as a database for, e.g., customer / user information, encryption keys and user permissions.

- **Policy Control Function (PCF)**: The PCF enforces policies regarding different data flows or users in the network. This plays an essential role in implementing QoS in 5G networks.
- **Access Management Function (AMF)**: The AMF manages the registration, reachability, connection and the mobility of users in the 5G network.
- **Network Slice Selection Function (NSSF)**: The NSSF is responsible for managing different network slices within the 5G network (network slicing is explained in detail in the following).
- **gNodeB**: In simple terms, a 5G base station is called gNodeB and is responsible for physically transmitting the 5G signal called NG-RAN (NG Radio Access Network) or simply *New Radio*.

To enable QoS in the 5G network, network slicing in conjunction with QoS flows are utilized [15]. Network slices are virtual networks on top of a single physical infrastructure and enable traffic separation and QoS. They are defined and configured within the NSSF. Example Slice/Service Types (SSTs) are the well-known corners of the 5G triangle: Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communication (uRLCC) and Massive Machine-Type Communications (mMTC). For example, different services can be handled by different network slices. Additionally, to ensure fine-granular QoS, multiple QoS flows can be defined within a network slice or globally for the 5G network, which represent logical flows through the 5G network. QoS flows are configured and controlled by the SMF in an end-to-end fashion from user equipment (UE) through gNodeB (gNB) to UPF. Communication packets are marked with a Flow ID mapping to a specific QoS flow and are handled accordingly by all components in the 5G core based on packet filters. Parameters defining a QoS flow are a 5G QoS identifier (5QI), a guaranteed flow bit rate (GFBR) and maximum flow bit rate (MFBR) as well as a maximum packet loss rate in uplink and downlink. 5QI are defined in the standard as services, which have pre-defined QoS parameters [16]. Example services are video streaming and mission critical data or more recent classes, e.g. *Low latency eMBB applications* like *Augmented Reality*. 5QIs comprise of the following performance characteristics: resource type (GBR or Non-GBR), priority, packet delay budget (PDB), packet error loss rate and others.

D. The Manufacturing-Network Mediator (MNM)

Traditionally, the MES only considers the availability of machines or personnel but not the communication network load during production planning, while the STING system gathers information about the network infrastructure but is not aware of the manufacturing applications which communicate via the network. In order to bridge the gap between the MES and STING, we introduce the Manufacturing-Network Mediator (MNM) that mediates between the MES, the STING and the 5G network.

The MNM has a database of all relevant manufacturing applications, each of which associated to its traffic pattern (see Fig. 5). More details about the manufacturing applications were given in section III-A. A production schedule created by the MES contains different manufacturing applications planned to be executed during different time periods. The MNM will map the manufacturing applications to their corresponding traffic patterns and forward them to the STING. As described in section III-B, the STING needs this information in order to perform realistic network stress tests.

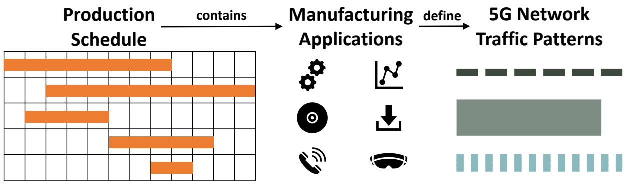


Fig. 5. Network traffic patterns can be derived from a production plan with known manufacturing applications.

Furthermore, the MNM derives network requirements from the traffic patterns and computes network configurations optimized towards these requirements. This network configuration uses QoS flow parameters and network slices as described in section III-C.

To sum things up, the MNM implements the combination between a) manufacturing processes in the MES, b) 5G network configurations and c) performance tests provided by the STING. The ideas behind this combination were outlined in the previous subsections. The next section IV gives more details about the MNM's interactions with other systems in our system model architecture.

IV. SYSTEM INTERACTION SEQUENCES

This section describes the interactions between the different components in our system model architecture in two different phases of production.

A. Phase 1: Initial network configuration and stress test

Our approach enables a demand-based network configuration procedure which is shown in Fig. 6 and will be detailed in this section.

Traditional production planning does not take communication network limitations into account. The more factory devices and applications communicate in the network, the more likely network congestions will occur that hamper the production. Hence, the manufacturing execution system (MES) is made aware of the fact that the network is a limited resource and gains the capability to make more accurate production schedules. One option to realize network awareness in the MES would be to simulate the network load for a production schedule based on theoretical assumptions. However, pure simulations struggle with common physical changes inside the production hall, which interfere with mobile networks, for example, moving equipment and materials. That is why we want to provide the MES with more realistic data derived from tests in the real network.

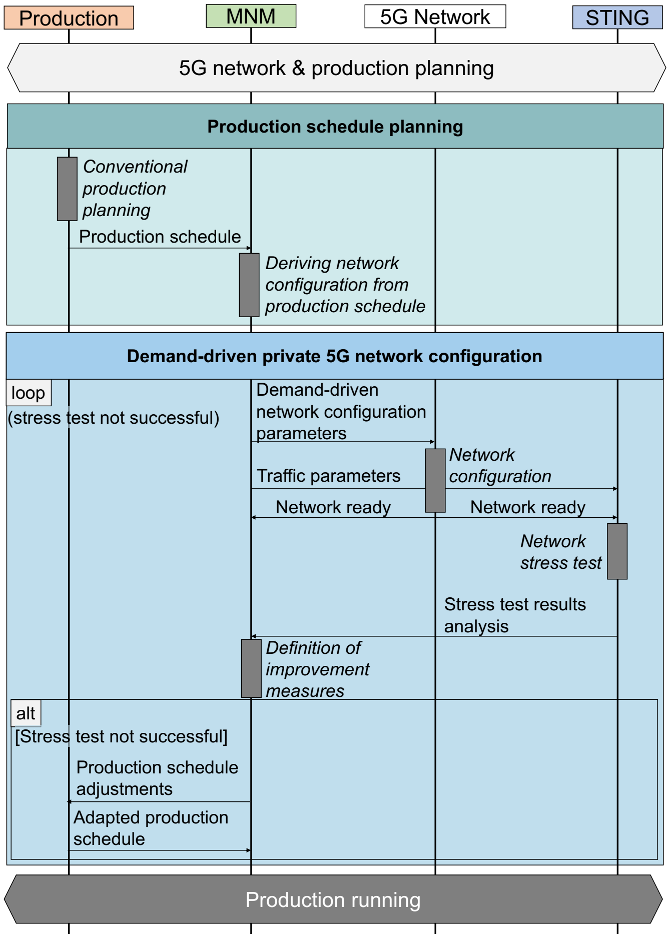


Fig. 6. Initial network configuration procedure prior to production schedule execution.

Initially, the MES plans the next production schedule the traditional way, i.e., ignoring the communication network and only regarding the availability of machines, materials and personnel. It provides the production schedule to the MNM, which in turn derives network requirements and traffic patterns from the schedule (see Fig. 5). The MNM computes a network configuration respecting the requirements and applies it to the 5G network. In modern 5G networks, particularly private campus networks, the correct configuration of the network will play a major role, especially when implementing QoS [17]. The configuration for that includes elements such as time division duplex (TDD) patterns, bandwidth parts, network slices, QoS flows and more. These parameters greatly impact network performance, especially network slices and, in conjunction, QoS flows. The first step in such a network planning process is to provide an initial configuration based on the application's requirements. In our approach, these requirements are derived by the MNM from the production processes managed in the MES. While traditional network planning ends here, in production environments, this will not be enough because these change from time to time, both physically (e.g., rebuilding or adding production lines) and logically (new processes requiring more data rate in the uplink). This means that adjustments to the network configuration are required after important changes in manufacturing. For example, the process of integrating a new production line would mean that a new network slice or QoS flow is required and configured. To validate the configuration, stress testing with STING can be conducted in order to assure that the network meets the new requirements.

Furthermore, the MNM forwards the traffic patterns to the STING system. STING performs a stress test of the productive 5G network by simulating traffic patterns of the planned manufacturing applications and meanwhile monitoring the network's quality of service. The STING system receives network performance requirements from the MNM, which are generated from production schedules of the MES (see Section III-D). The resulting number of applications, devices and traffic characteristics are emulated and evaluated in the initial network configuration. The system will evaluate active performance results containing achieved throughput, latency, packet error rate (PER) per application and signal quality parameters such as reference signal received power (RSRP) and reference signal received quality (RSRQ) per node and reports the networks suitability back to the MNM. The MNM can use this information to evaluate the initial production schedule and network configuration and make adjustments if needed.

We assume that the production is paused during the whole stress test and hence the communication network is utilized predominantly by the stress test traffic. This is an idealized assumption because, in practice, there are tasks spanning over several production schedules without any breaks in between. However, after major alterations of machines or production halls, there are usually time periods in which considerably less communication occurs and that can be used for stress tests.

If the stress test is passed successfully, the network will fully support the production schedule and production may begin. Otherwise, the stress test shows that the network will be a bottleneck and disturb the production schedule. In this case, the production schedule should be manually adjusted in the MES to reduce the resulting network requirements. This can be achieved by postponing some manufacturing applications, but also by, e.g., reducing polling intervals or reordering concurrent production steps. As mentioned in Section III-A, the communication behaviour of any manufacturing application and any manufacturing-related system must be respected. This means that in this description, the production schedule does not only include machines, but also, e.g., remote maintenance sessions. Therefore, it can be sufficient to postpone only an AR-based remote maintenance session instead of adjusting production orders. After the production schedule, or application schedule is adjusted by the MES, the MNM might adjust the 5G network configuration accordingly.

Subsequent to this process, the production line can go online with a highly reduced risk of potential failures in the production process due to the wrong dimensioning of communication resources.

B. Phase 2: Monitoring in running Production

Following the initial network configuration prior to the execution of a production schedule, the network performance has to be monitored during the running production as well to avoid network failures. This procedure is depicted in Fig. 7 and mainly consists of three functional blocks.

- **Regular STING Status**: During production, the STING keeps monitoring the 5G network's quality of service and periodically reports its status to the MNM.
- **Anomaly Report**: In order to detect unexpected network congestions early and inform the MNM about potential upcoming issues, STING directly reports exceptions to the MNM so that it can determine possible counter measures. Since the network was stress-tested before, unexpected congestion problems are assumed to be rare. However, one cannot rule out new sources of interference which were not present during stress testing. To enable this, the STING system will be able to use a software defined radio (SDR) interface to detect and observe network traffic and interference anomalies in the used frequency band.
- **Event-driven Stress Testing**: If production conditions change, STING can estimate the possible traffic load and the networks ability to fulfill the production demand. It then actively emulates and tests the updated traffic patterns if they are possible with the current network. If unexpectedly, a bottleneck occurs, the test is stopped immediately and the bottleneck gets reported to the MNM to initiate countermeasures.

With constant reporting from STING, the MNM has the possibility to, e.g., reschedule uncritical applications in order to avoid further channel congestion, rearrange critical applications to less interference-prone locations on the shop floor, or modify network configurations on the fly [17] if necessary.

V. CONCLUSION & OUTLOOK

In this paper, we have introduced an approach to combine manufacturing processes and a private 5G network, so that production planning and changes on the shop floor have an impact on network (re-)configurations. A system model architecture was described that comprises manufacturing-related systems, 5G network components, a network testing tool, as well as a mediator component that combines the manufacturing-related and network-related systems. These systems interact with each other in two phases: initial network configuration and monitoring in running production.

In the next project phase we will construct a demonstrator of our system model architecture and test it using a 5G campus network in one of Weidmüller's factories, so that this concept paper's architecture will be realized in a real manufacturing environment. In succeeding publications we will share our findings from the realization and discuss the lessons learned for industrial 5G campus networks.

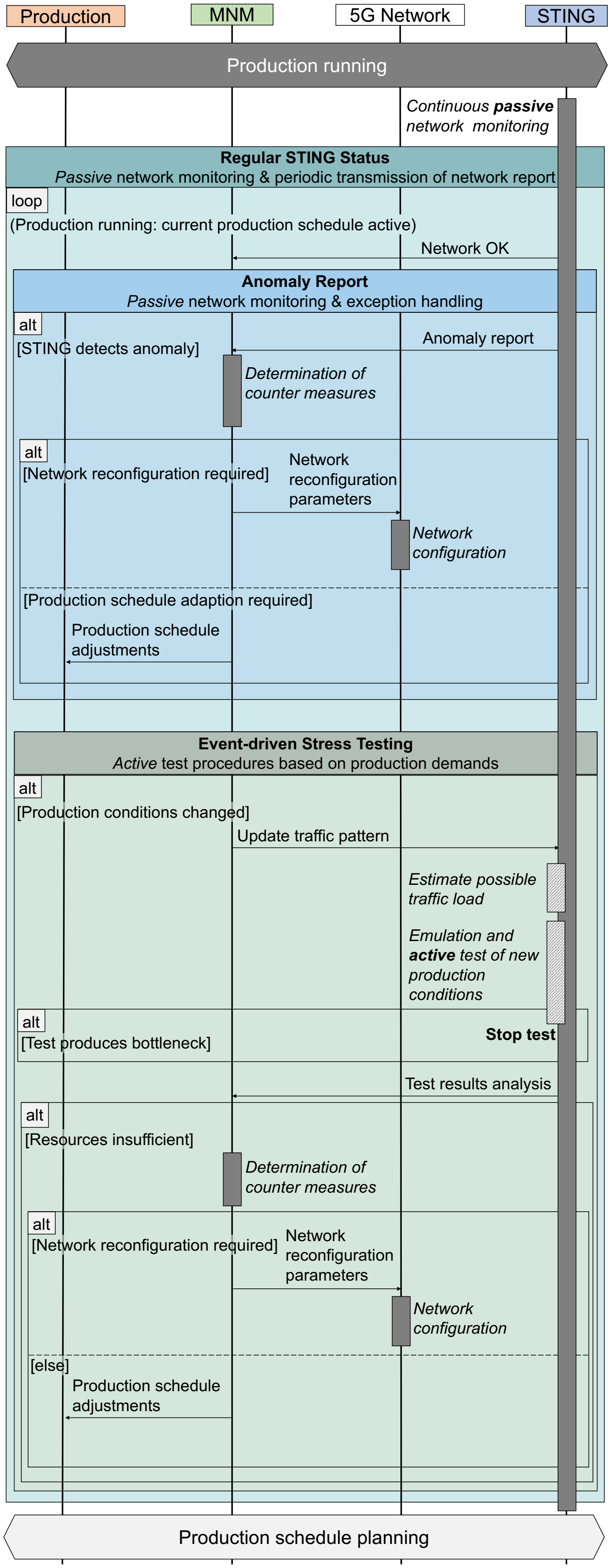


Fig. 7. Network monitoring procedure during running production.

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