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DYNAMIC SPECTRUM MANAGEMENT FOR 6G NETWORK-IN-NETWORK CONCEPTS

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ABSTRACT

Flexible, self-organizing communication networks will be a key feature in the next mobile communication standard. Network-in-Network (NiN) is one important concept in 6G research, introducing sub-networks tailored to specific application requirements. These sub-networks may be dynamic, i.e., they may appear, disappear, or even move throughout the network. Moreover, sub-networks may operate within a shared frequency spectrum, thereby requiring coordination among them. We demonstrate the concept of Dynamic Spectrum Management (DSM) for future 6G networks that dynamically (re-)allocates spectrum according to active sub-networks in the shared spectrum domain. Resilient control plane connectivity between sub-networks and the DSM is provided by the self-organizing routing protocol KIRA, enabling the aforementioned coordination. This demonstration presents an integrated solution of the DSM concept, providing increased flexibility to support diverse industrial applications and their individual performance requirements simultaneously within the context of a cyber-physical production system (CPPS). For the sub-networks, we use specifically designed hardware for wireless real-time communication and couple them with a network emulation. By switching sub-networks on and off, one can see that the DSM dynamically manages the spectrum allocations for them and that KIRA provides the required connectivity.

Keywords 6G, Spectrum Sharing, Self-organizing Networks, CPPS

1 Introduction

Highly flexible networks will play an important role in wireless communication networks of the future. They enable them to meet the increasing demand for data transmission with ever more specific requirements [1]. The introduction of Non-Public Networks (NPNs) in the 5G standard is an important basis for this. In addition to usual network operators, private companies can now also operate 5G networks in special frequency bands, e.g., for communication in production facilities. This opens up many new applications, but also new challenges. For future 6G-NPNs, it will therefore be necessary to share limited spectrum with all operators and users to further develop the application scenarios [2], [3]. In the presented demonstration, Dynamic Spectrum Management (DSM) is introduced as a solution concept for the identified problems. It combines previous work in the field of Network-in-Networks (NiNs) [4] and control plane connectivity for 6G [5] into an integrated DSM solution.

2 Background

2.1 Network-in-Networks

The upcoming 6G standard will increasingly focus on flexibility and simplified operation, which will be supported by self-organizing networks, i.e., operating without manual configuration or intervention. An important step towards this are so-called NiN, in which several mobile networks (sub-networks) are operated in the same coverage area, but with less transmission power, for example. These sub-networks are independent cellular communication systems that can be adapted to specific requirements. They offer significant advantages over non-cellular standards such as WiFi, especially in terms of robust communication due to higher network determinism [4]. In the NiN domain, multiple sub-networks can exchange user data via a shared backbone network. Coordination between the various stakeholders is therefore an inherent necessity.

In this demo we realize DSM using a simple centralized approach featuring a centralized Spectrum Manager (SM) and decentralized sub-network controllers (SNCs) to meet this increased demand for coordination. The SM dynamically accommodates sub-networks with different configurations and Quality of Service (QoS) requirements or multiple private mobile networks operated by different providers in shared spectrum scenarios. This sub-networks are connected via a master node to the backbone network. On the master node the deployed SNC sends the sub-network's requests for specific spectrum to the central SM, receives a negotiated spectrum configuration and forwards them to the sub-network, thus forming the basis for the exchange of user data. In this demo we chose a centralized approach for its simplicity. A decentralized approach in which the SNCs discover each other and communicate directly in a peer-to-peer-like fashion to reach consensus on how to distribute the available spectrum would potentially have better resilience, as it does not have the single point of failure of a central SM.

Ensuring trustworthy communication between all parties in the network is crucial, especially when user data is exchanged between different operators [6]. 6G NiN will enable application-oriented communication that can adapt dynamically to changing requirements through the DSM.

2.2 Connectivity and Discovery using KIRA

The coordination needed for the DSM requires communication through the shared backbone. The resilience of the connectivity enabling this communication is especially important for the operation of the DSM (and therefore also the operation of the sub-networks). It needs to be available even under network dynamics. In this demonstrator we use the routing protocol KIRA [5] to provide connectivity among individual sub-networks and all other nodes of the backbone. KIRA provides scalable, resilient, and self-organizing control plane connectivity as basis for a self-organized operation of the DSM. Additionally, it also supplies a simple discovery mechanism based on an integrated distributed hash table (DHT). This allows nodes to register under well-known names enabling sub-networks to discover the central SM.

3 Application Scenario: Cyber-physical production system

The DSM with its central SM is suitable for a wide range of applications. As manufacturing systems evolve towards Industry 4.0, networking of cyber-physical production systems (CPPS) and the integration of data into Digital Twins (DTs) are crucial [7, 8]. However, the different industrial applications have different requirements for communication networks. For example, closed-loop machine control systems have very high requirements for Ultra Reliable and Low Latency Communications (uRLLC) but require low data rates [4]. In contrast, capturing sensor data from a process has

Figure 1: NiN concept exemplified by a Computerized Numerical Control (CNC)-machine with sensors

lower real-time requirements but requires higher data rates. Different configurations of NiNs, such as Enhanced Mobile Broadband (eMBB) or uRLLC, allow them to be customized specifically to their applications.

DSM enables a new level of reconfigurability and flexibility in CPPSs. Through the central SM, sub-networks in highly dynamic CPPS can be added or removed as needed, ensuring that the available spectrum is always precisely adapted to the applications within a manufacturing system. Due to its very demanding Key Performance Indicators (KPIs), such as latency and jitter, a CNC machine tool featuring a virtualized machine control as part of a CPPS is considered in this demo.

As part of a Networked Control System (NCS), the controller of the CNC machine tool is operated on an edge device. The machine considered in this demonstration consists of actuators (servo motors, spindle), sensors (emergency stop, end switches), and a controller and communicate within the bandwidth-limited 5G NPN with an available spectrum of 100 MHz between 3.7 GHz and 3.8 GHz. The CNCs power electronics consisting of sensors and actuators are wirelessly connected to the edge-based controller via specifically designed hardware with a token-based communication system. Simultaneously, the milling process is monitored by various sensors. These sensors ensure that a DT has the relevant additional information to monitor the process based on real-time data from the CNC controller and to analyze it. In addition to vibration and acoustic sensors, sensors for ambient temperature and humidity were deployed.

As shown in Figure 1 and Figure 2 the setup consists of two sub-networks, the peer-to-peer sub-network 1 (SN-1) between the CNC-controller and the CNC machine, and the sub-network 2 (SN-2) for sensor data collection. Both sub-networks share the available spectrum, with two separate networks having individual configurations. As the sensor data in SN-2 require higher data rates, its network uses 60 MHz of the available spectrum, while SN-1 uses the remaining spectrum. These sub-networks, and the DT host are connected to a shared backbone in which KIRA establishes connectivity enabling communication with the central SM.

4 Demo Setup

The demonstrator consists of different parts (see Figure 2 and 3): an emulated backbone network, which can also be implemented as an real hardware deployment, as well as two physical NiNs and an additional physical host running a DT of the CNC environment.

4.1 Backbone Network

The backbone network consists of a set of routers that is emulated using containernet [9] on a separate host. Three containers of the emulated network are connected to one of the physical parts (sub-networks and DT node), through virtual links separated through VLANs using a VLAN-capable switch. Within this backbone, all nodes (physical and emulated) run a KIRA routing daemon that establishes IPv6 connectivity between all nodes. The demonstrator features a visualization of the backbone showing how KIRA establishes connectivity and how its DHT is used to discover the SM.

4.2 Network-in-Networks

The NiNs are implemented using Raspberry Pis (RPIs), each RPI is acting as a master node for the sub-networks behind it. A SNC on the RPIs is responsible for communicating with the SM via KIRA, it registers the spectrum requirement, and receives a corresponding response from the SM following an internal negotiation process. The actual sub-network, which in this demo consist of specially designed hardware (see Figure 3) for data exchange based on a token-based transmission protocol in the frequency range from 3.7 GHz to 3.8 GHz, are connected to the RPIs. The sub-network SN-1 is responsible for the communication between Field Programmable Gate Array (FPGA) and CNC machine, and SN-2 for the data exchange of the individual sensors.

4.3 Self-Organizing Dynamic Spectrum Management

The DSM is realized as a simple client-server architecture: a spectrum manager for simplicity also running on the DT node stores its IPv6 address (which was randomly generated by KIRA) in KIRA's DHT under the key "dynamic-spectrum-manager" and waits for connections. The SNC on the RPI performs the respective DHT fetch and connects to the spectrum manager. The spectrum manager then allocates spectrum according to the currently connected NiNs and sends appropriate commands back to the SNCs, which (re-) configure the sub-networks. This way the sub-networks do not need any special prior configuration, e.g., a particular address of the spectrum manager. As a result, if one of the two networks fails, the remaining network is reconfigured to use the spectrum of the failed network. As shown in Figure 3, the distribution of the spectrum is visualized on a dashboard in our demonstration. The DSM detects this failure and initiates the reconfiguration of the remaining network. The following table 1 illustrates the logic of the network of our setup.

Table 1: DSM Logic of the demonstration

	CNC Spectrum	**Sensor Spectrum**
Both running	40 MHZ	60 MHz
Sensor Network unavailable	100 MHz	0 MHz
CNC Network unavailable	0 MHz	100 MHz
Both unavailable	0 MHz	0 MHz

5 Demo Walkthrough

The demonstration shows the integration of the DSM into a real NiN setup and the reaction of the system to changes within the network structure (see Figure 3). As already explained in Section 4, dynamic adaptations to network requirements, e.g. in the production environment, can be realized in this way. The demonstration is divided into three different components:

- NiN: Visitors can interactively switch on/off individual sub-networks and observe resulting adjustments by the DSM. The SM initiates the reconfiguration of the networks and assign new frequencies, executed by the SNC.
- DT: Operational capability and performance of NiNs will be demonstrated as a DT using the industry-oriented application of a CNC machine with sensor data evaluation.
- Visualization: Control and configuration in the shared backbone are displayed both for the DSM as a dashboard of the current configuration and for KIRA's connectivity.

6 Conclusion and Future Work

In this paper a novel self-organizing Dynamic Spectrum Management for 6G networks was introduced and its application in a NiN setup is demonstrated. The proposed DSM efficiently allocates spectrum to fulfill various application

requirements in Industry 4.0 and ensures robust communication. The demonstration with a CNC machine tool highlights the adaptability and reliability of this approach. Future work will focus on the development of decentralized DSM solutions and the integration of more sophisticated dynamic spectrum management techniques to support nomadic networks.

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Figure 2: Demo Architecture (SM = spectrum manager)

Figure 3: Demo Setup