Master's Thesis

Czech
Technical
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in Prague

F3

Faculty of Electrical Engineering
Department of Radioelectronics

Optimization of the Remote Robot Control via Mobile Networks

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Supervisor: Ing. Jan Plachý, Ph.D.
Field of study: Electronics and communications
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MASTER‘S THESIS ASSIGNMENT

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II. Master’s thesis details

Master’s thesis title in English:

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Master’s thesis title in Czech:

Optimalizace mobilních sítí pro vzdáleného řízení robotické jednotky

Guidelines:

Familiarize yourself with the topic of remote robot control via 5G mobile networks and ultra reliable low latency communication. Study mobile network architectures, communication protocols and platforms for mobile network emulation. Setup a testbed for remote robot control through two mobile networks separated by a geographical location, that introduces an additional communication delay between the mobile networks. Design a suitable solution for deployment of mobile network functionalities with focus on both radio access network and core network. Design an allocation of communication resources to provide a low communication latency with a high reliability. Evaluate the proposed solution in an emulated mobile network and compare with existing solutions.

Bibliography / sources:

[1] B. Sonkoly, et al. '5G applications from vision to reality: Multi-operator orchestration.' IEEE Journal on Selected Areas in Communications 38, no. 7 (2020): 1401-1416.
[2] M. Uitto, M. Hoppari, T. Heikkilä, P. Isto, A. Anttonen, and A. Mämmelä. 'Remote control demonstrator development in 5G test network.' In 2019 European Conference on Networks and Communications (EuCNC), pp. 101-105. IEEE, 2019.

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III. Assignment receipt

The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt Student’s signature

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I want to thank Ing. Jan Plachý, Ph.D., for his benevolent guidance, prompt help and his time during the whole process.

Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses

Prague, January 9, 2024

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

V Praze, 9. ledna 2024

Abstract

The 5G mobile networks provide very low communication latency, therefore, enabling services such as URLLC. One of the URLLC services is Tactile Internet, which aims at enabling remote operations with haptic data, such as touch and feel, to the humans. 5G does not enable all Tactile Internet use cases, but Remote Control is available. In Remote Control applications such as Remote Robot Control both the controller (human operator) and robot can be mobile. In many cases, either only the robot or the controller are connected via mobile network. However, in many cases, both the controller and the robot can be connected via geographically separated mobile networks. Thus, in this thesis we develop a solution for optimization of two geographically separated 5G mobile networks through joint resource allocation. Proposed solution leverages O-RAN xApps within RIC framework, to access the mobile network information and optimize both mobile networks providing connectivity of the controller and the robot. To test the designed concept of xApps, implementation in open source mobile network emulator with standard E2SM is envisioned. However, as of writing of this thesis none of the open source mobile network emulator have the features necessary for implementation of the proposed solution available, thus only high level implementation is provided.

Keywords: Remote Robot Control, 5G Mobile Network, E2E Delay Optimization, Resource Allocation, RAN Intelligent Controller, xApp

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Abstrakt

Mobilné siete piatej generácie poskytujú pripojenie s veľmi nízkym komunikačným oneskorením. Vďaka tomu je možné 5G sieť použiť na prenos s požiadavkami URLLC. Jedna zo služieb URLLC je takzvaný Taktilný Internet, ktorý je založený na poskytovaní vzdialeného ovládania so spätnou väzbou s úplnym hmatovým vnemom. 5G sieť úplne nepodporuje Taktilný Internet, ale vzdialená kontrola podporovaná je. V aplikáciách ako je vzdialená kontrola robotických jednotiek, môže dochádzať k pohybu zariadení aj na strane operátora a aj na strane robotickej jednotky. Často sa pri vzdialenom ovládaní hýbe iba robotická jednotka, ale sú aj prípady kde dochádza k pohybu operátora aj robotickej jednotky súčasne. Preto sme vypracovali riešenie optimalizujúce obe geograficky vzdialené 5G mobilné siete. Optimalizácia je postavená na vzájomnom prideľovaní prostriedkov. Využívame O-RAN xApps s RIC frameworkom na optimalizáciu obidvoch mobilných sietí. Aby sme overili náš koncept návrhu postavený xApps predstavujeme implementáciu v open source emulátore mobilnej siete za využitia štandardných E2SM. V čase písania tejto práce žiadne z dostupných open source emulátorov mobilných sietí neposkytuje funkcie potrebné k implementácií navrhovaného riešenia. Preto predstavujeme iba konceptuálny návrh implementácie.

Klíčová slova: Vzdialené ovládanie robotickej jednotky, 5G mobilná sieť, Optimalizácia E2E oneskorenia, Priraďovanie prostriedkov, RAN inteligentný kontróler, xApp

Překlad názvu: Optimalizace mobilních sítí pro vzdálené řízení robotické jednotky

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Chapter 1

Introduction

Mobile networks have changed significantly from their first deployments in the 1990s. In their inception mobile networks were intended to be used mainly for wireless call service. If we compare the scope and technology of legacy Second Generation (2G) network with the current 5G network, the differences are immense. Although the underlying concept remains the same, the provision of wireless connection is done via base stations deployed following cellular structure (where the name of cellular networks originates), the 5G network aims to provide a general framework for any network service imaginable. This has led to a need of novel approaches to satisfy the service needs. Thus, the network architecture has been revised leading to more focus on software that could be run on a generic hardware. The revision relies on the concepts of Radio Access Network (RAN) softwarization, Network Function Virtualization (NFV) and Cloud Computing to realize necessary network changes [13].

5G services are envisioned to provide services such as NFV Infrastructure as a Service (NFVIaaS), Network as a Service (NaaS), Virtual Network Function as a Service (VNFaaS) or even Software as a Service (SaaS) [13]. The 5G network design includes Management and Orchestration (MANO) component to provide automated service creation, management and enforce adherence to contracted service parameters [14]. MANO is a key part in providing network slices to network services. Network Slice can be described as part of virtualized End to End (E2E) network resources and is the fundamental part of the 5G service based network concept.

Research & Development of the 5G network is expensive and thus requires joint effort of standardization entities, academia and industry. 3rd Generation Partnership Project (3GPP) is the international cooperative initiative for mobile network standardization. It consists of world wide standardization entities and market representation partners. From its creation in 1998 it has produced and maintained standards which shape the development of mobile networks. O-RAN alliance a joint collaborative entity which connects industry partners with academic institutions with aim to create Open, HW agnostic 5G RAN a reality. The O-RAN alliance follows 3GPP standards but it also creates and describes their own standards which build on top of standards defined by 3GPP. As a part of O-RAN MANO framework RAN Intelligent Controller (RIC) is defined, which interfaces with RAN instances to provide a standardized way to expose and control RAN. It also enables creation of custom control applications called xApps that use the RIC to access RAN functions and perform desired control actions.

One of the emerging applications that builds on the 5G is the Tactile Internet. Tactile Internet considers human to be in the Loop system, such as human operated remote device (robot). The feedback and control information is transferred through the mobile network. However, the true challenge of the tactile internet is both the sheer amount of data that needs to be transferred and the E2E delay requirements. The feedback data intended for the human operator creates a full sensory experience which is thought to require connection speed in order of Tbps and Round Trip Time as low as 1 ms with reliability as high as 10^{-7} [15]. These requirements are beyond the capabilities of 5G network [15].

This thesis is focused on application which is a precursor to the Tactile Internet - Remote Control. Remote Control transfers less data and is not as stringent in latency requirements which makes Remote Control in 5G mobile networks feasible [16, 17, 18, 19, 20, 21, 22]. However, improvements of the 5G network are necessary to provide full and seamless support for Remote Control applications in real deployments with dynamically changing channel quality and real data traffic. Some of the research aims to solve problem of coexistence of different applications by effective resource allocation and prediction [23, 24, 25, 26]. However, we present a solution for the Remote Control application with the aim to improve performance of E2E connection to be then used as basis for Remote Control laboratory deployment. The solution uses RIC in combination with xApp of our own design to optimize RAN for Remote Control.

Chapter 2

Mobile Networks

The main parts of the mobile network architecture are the Core Network and Radio Access Network. Each has a different main function. Generally, the Core Network is responsible for higher network layer tasks such as management, control and authorization of User Equipment (UE). Whereas, RAN operates the lower network layers providing radio access, resource division and multiple access for UEs. The 5G mobile network architecture is shown in Figure 2.1 which illustrates both RAN and Core. Core functions are represented by narrow white rectangles and are enclosed within a white dashed line in the Figure 2.1. Each of the core functions has their specific responsibilities that provide the whole control service set of the core network. The picture also contains names of interfaces core functions use for communication. The small part in the bottom left of Figure 2.1 is RAN and 5G UE. 5G UE connects over provisioned wireless resources to gNB. The UE wants access to Data Network to access the internet or other services. Therefor, RAN interfaces with the User Plane Function (UPF) to provide UE connection to the Data Network. The UPF provides and controls data flows of the connected UE .

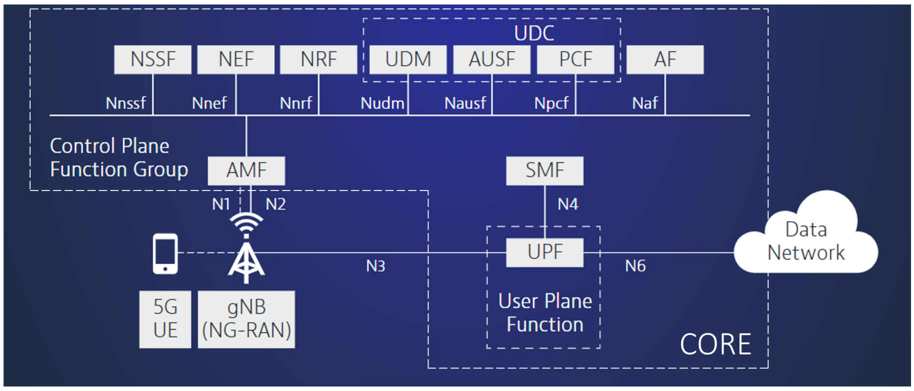

Figure 2.1: 5G architecture adapted from [1].

2.1 Radio Access Network

RAN not only needs to manage radio resource sharing but also prepares the user data so that the transmission is reliable and communication resources are effectively used. In addition to User data RAN also contains control mechanisms that define the behavior of RAN layers and interface with the Access and Mobility Management Function (AMF) core function. In Figure 2.2 two planes are shown: data (or user) plane and control plane. Data plane transports user data, is responsible for data encapsulation and transmission parameters. The way in which data plane operates is decided by the control plane.

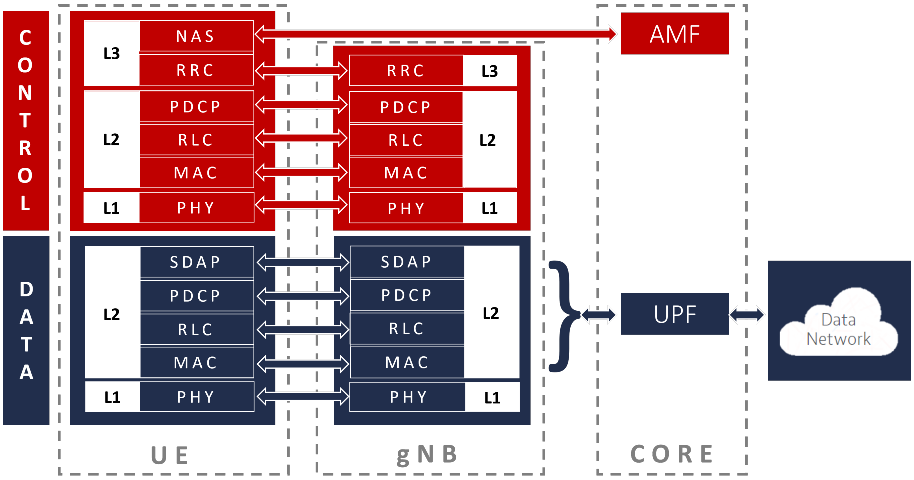

Figure 2.2: RAN protocol stack adapted from [2].

2.1.1 Physical layer

The mobile network communication is a form of wireless communication. In the wireless communication the propagation medium (the Ether) is mostly air. We rely on antennas to use the propagation medium for transmission of electromagnetic waves. Antennas convert signal propagating along wired conductor to propagate in the wireless medium. The signal that goes to the antennas needs to be prepared, and this happens in the Physical layer. The physical layer takes care of coding, modulation, resource mapping and antenna mapping. In other words, the idea behind Physical Layer is to facilitate mobile connection which is reliable and has efficiently allocated frequency resources. Frequency spectrum is a limited resource, it is shared not only amongst users of the same wireless service but even amongst different services altogether. Therefore, it was decided that parts of the radio spectrum should be allocated to given services. The radio spectrum is divided into licensed and unlicensed parts. The mobile network operates in the licensed part and the network operators compete to buy parts of the licensed spectrum in each country. Frequency bands used in the previous generations of mobile networks are used in 5G as well: Low-bands (below 1 Ghz), Mid-Bands (1 - 2.6, 3.5 - 6 GHz). However, 5G RAN aims to utilize additional previously unused spectrum in the High Band region (24 - 40 GHz). This increases the usable frequency spectrum and so increasing the available cell throughput. Sharing of the spectrum within the mobile network is performed in several domains: spatial, time and frequency. Spatial separation is simply division of space that is supposed to have mobile network coverage into smaller sections called cells. Each cell has its BS and frequency allocation which can be reused in cells which are far enough to not cause co-channel interference (interference on the same channel). Each cell provides connectivity to a set of devices called User Equipment (UE). All the UEs within the same cell share the resources of the given cell amongst each other. There are several ways in which the resources can be shared, called Multiple-Access Schemes. Time Division Multiple Access (TDMA) gives each user full bandwidth for a given time, then another user gets to transmit. Analogously, Frequency Division Multiple Access (FDMA) gives each user a part of the spectrum to use without a time restriction. Combining both methods, that is giving each user a portion of the frequency spectrum and time gives us the Orthogonal Frequency Division Multiple Access (OFDMA). OFDMA is used both in Fourth Generation (4G) and 5G. It uses large number of closely packed sub-carriers which span the whole 5G frequency spectrum. 5G allows to set frequency width of the sub-carriers which then influences other fundamental Physical Layer parameters. 5G Numerologies describe how the choice of sub-carrier width affects fundamental transmission times called symbol times. The whole OFDMA structure is a grid where the x axis represents transmission time and y axis represents frequency allocation. In the grid we define the smallest time interval (symbol) as one symbol and smallest frequency Bandwidth (BW) as one sub-carrier. We call this grid the resource grid. Resource Element (RE) is one symbol long and one sub-carrier wide. However, the RE, represents only negligible part of the whole resource grid. Therefore, a frame structure is defined to help navigate the time axis of resource grid conveniently. These structures are defined in the frame structure (in descending size order): frame, sub-frame, slot and symbol. The frame structure is different for each of the 5G numerologies. However, length of frame and sub-frame is always 10 and 1 ms respectively. What changes is the length of slot in ms but in terms of symbol length the slot is always 14 symbols long. Physical layer resources are scheduled by the Medium Access Control (MAC) layer.

2.1.2 Medium Access Control layer

In the mobile network protocol stack the MAC layer is directly above the Physical layer. Scheduling of allocated time, frequency or both is done in scheduler that is a part of the MAC layer Furthermore, MAC layer incorporates procedures such as scheduling request, semi-persistent scheduling and other. Scheduling request is the standard way for the the UE to request resources for Up-link (UL) transmission. It consists of several steps that allow the base station to gather all the required information to schedule resources for the transmission described in Figure 2.3.

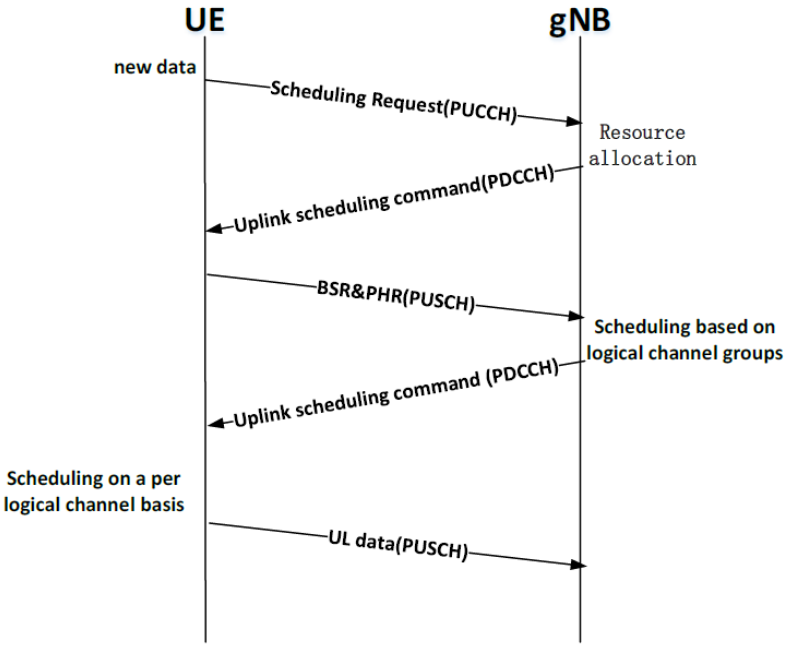

Figure 2.3: Uplink scheduling request as a part of standard Dynamic Scheduling procedure reproduced from [3].

When a connected UE has data to transmit it sends a scheduling request on Physical Up-link Control Channel (PUCCH). The return message from the gNB contains information about UL-Physical Up-link Shared Channel (PUSCH) resources for transmission of Buffer Status Report (BSR) and Power Headroom Report (PHR). These reports are used to determine the allocation size and transmission power levels of the UE. Now the gNB has enough information to send a scheduling command that informs the UE when and how to transmit the data in its buffer [3]. This method is used because it effectively uses resources but the UE pays with additional delay. Configured Grant and Semi-Persistent Scheduling procedures represents an alternative to standard UL or Down-link (DL) procedures respectively. It provides an alternative that reduces overhead and delay for transmissions with periodic traffic patterns. However, these procedures settings are the responsibility of the Radio Resource Control (RRC) control layer.

2.1.3 Radio Resource Control layer

The Radio Resource Control (RRC) is protocol used for control of the RAN radio stack [27]. It stores and negotiates UE context in terms of parameter settings of lower layers for the UE . The most important part of the RRC is the UEstate machine definition and its tracking for each UE . The RRC state is a tool that ensures UEs that do not need resources do not burden the network.

In the case of the Configured Grant or Semi-Persistent Scheduling the information about future transmissions is shared using an RRC message with all the relevant parameters.

2.2 Core Network

The Core network is the main control system in the mobile network. The improvement that the 5G core network provides over 4G is that all its functions are to be virtualized in line with the aim to make the whole 5G network a service based system. Core Functions are parts of the Core network which responsible for controlling a certain mobile network function components.

In 5G there is a clear differentiation between data and control planes as visible in the Figure 2.2. However, Figure 2.2 does not show complete interaction between the control and data planes. The AMF gives the UE access to the network and manages cell handovers, i.e. mobility. To give UE access AMF interacts with the Authentication Server Function (AUSF) which authenticates the UE with the help of the Unified Data Manager (UDM) [28]. The UDM stores and manages data for a given user for any network service that needs it. After the UE has been authenticated the Network Repository Function (NRF) starts a discovery process to gather information about Network Function (NF) availability and then store them in a database called the NF Profile. NRF coordinates all the other NFs. The AMF is also an intermediary between UE forwarding session requests to the Session Management Function (SMF) which is mainly responsible for management of Protocol Data Unit (PDU) sessions [29]. The SMF is a direct control counterpart of the UPF which enacts SMF commands and provides the connection to the Data Network (Internet). The Policy Control Function (PCF) also interacts with the SMF to make sure Quality of Service (QoS) is being fulfilled, the UE is charged for the provided services and helps with the Network Slice management [30]. Network Slice could be generally described as a part of network resources reserved for a given service accessible by a pool of UEs. Furthermore, the Network Slice must adhere to certain parameters that are required by the associated service. Core function that is responsible for appropriate Network Slice selection for a given UE is called Network Slice Selection Function (NSSF).

2.3 O-RAN

As mobile networks development is relying more and more on software, O-RAN has been established to drive the mobile industry towards an ecosystem of innovative, multi-vendor, inter-operable, and autonomous RAN, with reduced cost, improved performance and greater agility [31]. O-RAN follows 3GPP standardization and builds on top of it, by focusing solely on RAN. O-RAN Alliance is an entity which was founded as a cross industry collaboration effort to oversee Open RAN creation with these objectives [4]:

1. Openness, interoperability and virtualization of RAN and its components

2. Minimizing the use of proprietary HW
3. Appropriate open-source Application Programming Interface (API) and interface specification

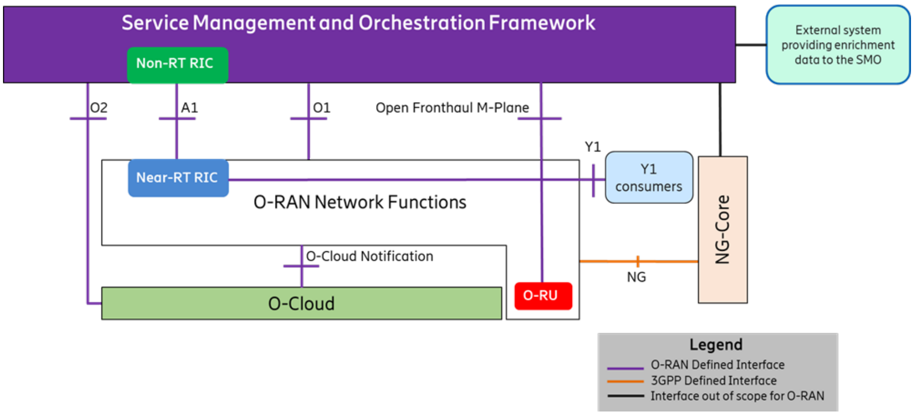

Figure 2.4: O-RAN high level architecture reproduced from [4].

The resulting O-RAN architecture delivers both on the O-RAN objectives and 5G shift towards anything as a service model. The key component in terms of accessing RAN functions is RIC - RAN Intelligent Controller. In Figure 2.4 both Non-Real Time RIC and Real-Time RIC are shown. Non-Real Time RIC is a part of the Service Management and Orchestration (SMO) framework with the purpose of creating policies which are then invoked by the much faster Near-Real Time RIC. Besides being the middle man between SMO and gNB, Near-Real Time RIC offers a general SW platform for RAN control and xApps. xApp is an independent third party SW that uses the Near-Real Time RIC platform to perform a set of specific RAN control actions or collects RAN parameter data. In our solution we develop xApps that run near both gNBs to gather RAN parameter values, perform RAN control and share traffic information with each other. The E2 interface facilitates information exchange between the gNB and Near-RT RIC and is described in detail several O-RAN standards. E2 Application Protocol (E2AP) is a protocol that is implemented on the E2 interface. It defines several elementary procedures to establish connection, gather data at given moments and control and modify RAN behavior. To access specific RAN parameter sets we choose an appropriate E2 Service Model (E2SM) which are able to access parameters specified in standards associated to a given E2SM. Moreover, developers can create their own E2SM to gather specific data or control RAN in a specific manner.

2.4 O-RAN RIC

RIC stands for RAN intelligent controller. Its main purpose is to expose RAN functions through E2 interface. The exposure serves as a platform for O-RAN

Operations and Maintenance and for developers offering a standardized and efficient tool for interfacing with RAN functions. RIC forms the foundation for xApp development. xApp is a third party program that controls RAN functions through the RIC platform. Conceptually, the RIC is consists of Non-RT RIC and near-RT RIC. The division is based on the control loop latency that can be achieved by both categories.

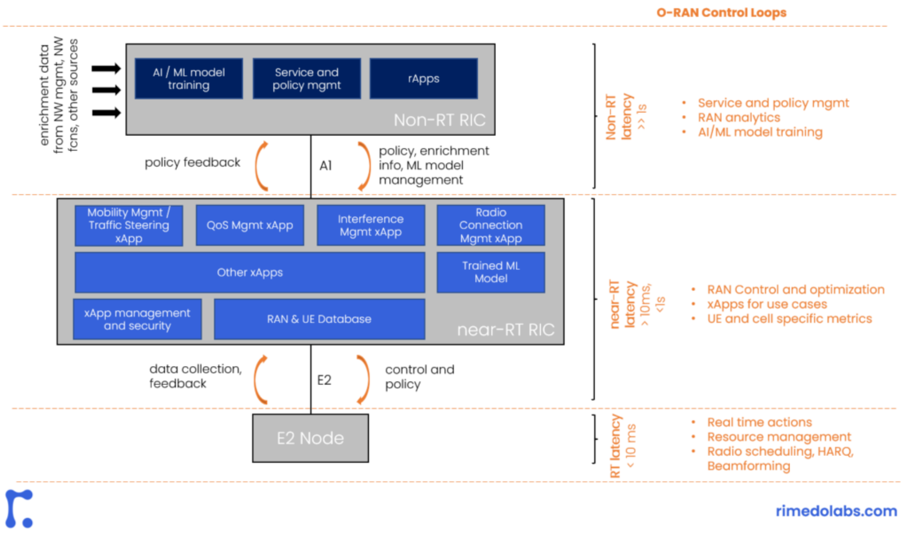

Figure 2.5: Non-RT RIC, near-RT RIC and E2 Node division with control loops illustration [5].

2.4.1 E2 Service Models

E2 Service Models (E2SM) define communication between gNB and RIC over the E2 interface. The O-RAN alliance has defined these standard E2SM models [32]:

1. Network Interface
2. Key Performance Monitoring
3. Cell Configuration and Control
4. RAN Control

Network Interface E2SM exposes network interfaces and allows modification of messages in these interfaces. Furthermore, the Network Interface E2SM can executes policies which alter network behavior [32]. Key Performance Monitoring (KPM) E2SM is a purely monitoring model which provides measurement reporting of selected RAN function parameters [32]. Cell Configuration and Control E2SM provides read and control access to "cell level" configuration and parameters. Finally, RAN Control E2SM provides access to such RAN parameter sets as L2 MAC State Variables, gNB Measurements or UE Context Information. Generally, RAN Control E2SM is meant to be used for modifying behaviour of RAN at a given time. In addition to the standard E2SMs it is possible to create custom models that provide functionality that is required and reaches beyond the standard.

RAN Control E2 Service Model

RAN Control E2 service model is a standard service model. It uses five RIC Services: E2 Report, E2 Insert, E2 Control, E2 Policy and E2 Query [9]. The Report Service acquires requested information from RAN based on a selected trigger event. It and can be used to obtain copies of RRC or other Network Control messages, RAN status information, E2 Node information, information about the cell or UE [9]. The Query Service is similar to Report Service in that it is used to acquire information. However, the Query Service does not use a trigger event; the information is retrieved on demand but the available RAN information is limited compared to the Report Service [9]. The Insert Service withholds RAN control action that is normally executed by RAN itself by setting up a trigger in response to a specific event. When the trigger is activated a message is sent to RIC to decide on the control action. The response is decided in RIC and sent using the Control Service. The Insert service is just a name for Control Service that is triggered by an event [9]. When there is no need for specifying a trigger we use the Control Service directly. Control Service can be used to access in Radio Bearer Control, Radio Resource Allocation Control, Connected Mode Mobility Control, Radio Access Control, Dual Connectivity Control, Carrier Aggregation, Idle Mode Mobility Control, UE to RAN UE group assignment, Measurement Report Configuration Control either as a single action or bundle multiple actions into one control message [9]. The Policy Service is useful when we need to change general behaviour of the RAN Control domains. There are two options that the Policy Service offers for RAN behaviour change. The first option is the Policy Service Control approach which is used to completely replace part of standard RAN behavior. The second approach is the Policy Service Offset which changes parameter(s) threshold for standard RAN behavior thus modifying RAN behavior. The scope of available RAN functions is nearly the same as for the Control Service [9].

Chapter 3

Tactile internet

In this application the human operator controls a remote vehicle, robot or another device using video captured on the controlled device as feedback. It is the first milestone in the realization of the tactile internet, which has strictly defined Round Trip Time (RTT) target and is set to support numerous sensors and actuators for feedback. The IEEE P1918.1 working group defines the Tactile Internet as “a network, or a network of networks, for remotely accessing, perceiving, manipulating, or controlling real and virtual objects or processes in perceived real-time” [33]. This definition is broad enough to encompass the whole range of specific applications and mentions the requirement for feedback necessary to achieve real-time perception. Technically describing the requirements of the tactile internet connection gives us the RTT around 1 ms to prevent cybersickness, the need for synchronization between the number of transmitted sensory signals and the video feedback and the reliability criterion of 10^{-3} to 10^{-7} failure rate based on the specific application [15]. These criteria are very hard to achieve and face not only technological obstacles but also the physical limit on the distance of such connection (RTT of 1 ms corresponds to 150 km distance between the nodes). Authors in [34] split the problem into 4 categories: haptic, intelligence, computational and communication challenges. Taking a remote surgery as an example the haptic challenges could be how to read all the necessary sensory information from the patient, how to encode the sensory data so that the latency is not increased [35], where to store the information when they arrive at the remote controller and how to construct the actuators so that the feedback and the action are fully actualized and precise so that no harm is done to the patient. To help mitigate the effects of momentary increase in the connection error rate or sudden increase in latency and to decrease latency during normal conditions a haptic predictor is utilized. The concrete function and design of such predictor form the intelligence challenges. Large amounts of haptic data needs to be processed while the prediction algorithm is running, this is not a problem. However, to do so without impairing latency in any way is and that is the computational challenge. From the perspective of the 5G network the communication challenges are the interesting ones. Reaching ultra-low latency, ultra-high reliability and high throughput at the same time is the requirement on the network. Disregarding all but one of the categories of challenges for tactile internet: the communication challenges, leaves us with the requirements for remote control. Although, the requirements are less stringent for the remote control they are qualitatively the same. To be exact tactile internet requires throughput in the order of Tbps, Bit Error Rate (BER) 10^{-3} to 10^{-7} and RTT of 1 ms, which, without the throughput requirement correspond to Ultra Reliable Low Latency Communication (URLLC). Previous generation of mobile networks were not capable of supporting URLLC but 5G is considered an enabler for this type of communications [36]. Flexible frame structure, a shortened minimum Transmission Time Interval (TTI) to 2 Orthogonal Frequency Division Multiplexing (OFDM) symbols, improved Hybrid Automatic Repeat Request (HARQ), new codes and beam-forming all play a role in providing the standing ground for URLLC [36]. However, achieving 10^{-5} error rate and below 1 ms delay is not a given when using the 5G-New Radio (NR). New highly reliable error correction codes provide 10^{-5} error rate for a single transmission (further increase causes very low data rates – the error-floor problem) combined with fast Modulation and Coding Scheme (MCS) selection methods constitute the first approach to reach the reliability criterion [37]. The second approach uses either unsolicited bursts of re-transmissions within confined time intervals or the fast HARQ which enables re-transmissions only after two mini-slots [37], [38]. To further increase the robustness re-transmissions can use different sub band or use dual connectivity to re-transmit using a different gNB [37], Packet duplication for URLLC in 5G dual connectivity architecture]. Using these methods warrants the URLLC reliability requirement fulfilment. To minimize the delay introduced by the network we must first understand its origin. Article [3] dissects the loop-back (UE to gNB and back) transmission latency an its origins. Authors divide the contributing partial delays into two groups based on adaptability: persistent and adjustable delay. Packet processing by the UE or the gNB belong to the persistent group, which is not interesting, because it cannot be affected by changing a network parameter. However, the delays from the adjustable group: up-link waiting for scheduling and resources, up-link transmission, down-link waiting for resources and down-link transmission are the focal point of the RAN optimization. The network parameters in question are sub-carrier spacing (frame structure), duplexing mode (Time Division Duplex (TDD) or Frequency Division Duplex (FDD)), service type URLLC/enhanced Mobile Broadband (eMBB) and UL transmission access type. The authors of [3] have determined that parameters optimized for the smallest loop-back latency in a sub-6 GHz band are 30 kHz Sub-Carrier Spacing (SCS), FDD and Uplink Grant Free Type 1 procedure. The resulting delay was 0.75 ms. Furthermore, the authors conclude that different SCS intervals are the main delay contributor in FDD duplexing mode.

3.1 Remote Robot Control

Remote Robot control or telerobotics refers to human operation of a remote robot. The mobile network is used to transfer both control signals and video feedback. From networking perspective the concrete application is irrelevant if the parameters for the communication remain the same. Telerobotics is used in instances where human operation is not possible or not desired for safety purposes. One of the emerging applications of remote robot control in the medical field is remote surgery.

3.2 Remote Surgery

Remote surgery could be classified as a subset of Remote Robot Control with life saving potential. The reason for adoption of remote surgery is to deliver the best medical expertise quickly to where it is needed without presence of an expert at location. This way the expert surgeon does not need to travel to the patient and the patient does not need to travel to the hospital for an urgent procedure. Simply a robot is taken to the patient and urgent, possibly life saving medical procedures can be done earlier. Another problem which could be solved by remote surgery is the lack of expert level medical specialists for a given procedure. A medical expert could perform surgery remotely from a different hospital without the need for travel. However, in this case wireless network connection probably is not necessary.

The portable robot would use mobile network connection with URLLC requirement for communication. Demonstration of remote laparoscopic surgery using 5G network connection was attempted in China in 2020 [22]. The distance between the surgeon operator and test animal carcass was nearly 3000 km. The transmitted data stream was composed of 4K real-time video and control signals for the "MicroHand" surgical robot. Customer Premise Equipment (CPE) was used to connect to the 5G network on both ends providing a throughput of 1 Gbps. Furthermore, Virtual Private Network (VPN) was set up to secure the data stream. The results were compared with a 100 Mbps connection through wired connection. Total average network delay was higher for the 5G case compared to wired connection with 264 and 206 ms respectively. The authors concluded that 5G could be used for remote surgeries because it provided total delay below 300 ms. Furthermore, authors reported 1.20 % packet loss ratio. Specific data on 5G connection reliability or 5G network settings were not included.

Chapter 4

State of the Art

4.1 Remote control

In the following section we present current research efforts regarding Remote Control in mobile networks. An article published in 2019 evaluated 5G Proof of Concept (PoC) radio for remote control applications [17]. The authors compared delay and jitter for video and control traffic separately using Wi-Fi, LTE Advanced (LTE-A) and 5G PoC. Two types of network traffic were considered: 720p video with H.264 encoding streamed by Real-time Transport Protocol (RTP) protocol and randomly generated User Datagram Protocol (UDP) traffic. 5G dwarfed the competition providing under 1.65 ms delay and jitter under 0.35 ms for both video and control traffic. In a similar article, authors measured E2E video latency in 5G network with varying UL congestion [39]. A single full-HD camera with SW encoder running on a Universal Serial Bus (USB) connected laptop was generating the video stream. Video server was located on the edge on the network forwarding the stream to video player through the 5G network. Two live video streaming protocols were tested Real-Time Messaging Protocol (RTMP) and Rapid Spanning Tree Protocol (RSTP)/RTP. The result shows a very similar result for both. The UE used TDD with 3/7 frame structure for UL and DL respectively. The capacity with the given setup was measured as 50 Mbps in UL. However, the results for congested UE UL show that when 90% of the UE UL capacity is reached E2E delay increases significantly; from under 200 ms to over 500 ms. Therefore, the authors conclude that the 5G network with their settings is not suitable for UL video streams with throughput higher than 40 Mbit/s for 60 MHz bandwidth. In a different article authors tested the readiness of 5G-RAN in real deployment for URLLC remote control [21]. The scope of the deployment was to test replacement of cable connections from the harbour Rubber Tie Gantry (RTG) Cranes with a 5G-URLLC wireless link. The harbour crane operators are sat at a centralized location with remote control functionalities. Network traffic in the system originates from the crane cameras and the operation controls. Constraints were set by the existing control system – the safety cycle which checks if the connection is stable and within parameters can be set from 16 ms up to 64 ms (this time is a full delay representing the processing and transmission). After this time has elapsed the message is assumed to be lost. The number of consecutive losses is between 2 to 6 safety request messages. If this number is reached the system performs an emergency shut down. The constraints on the actual control data are less stringent; set around the 0.5 s. The authors decided to separate traffic into critical control traffic and video traffic. They used two URLLC Layer 1 links with blind re-transmissions for the critical control traffic and an eMBB bearer for the video stream. Furthermore, the Band 7 at 2.6 GHz was used with BW of 10 MHz. The Physical Resource Block (PRB) grant for UEs was static and the higher layers were optimized for short packet traffic. The measurements also included 4G performance to demonstrate improvements in 5G. Both in lab measurements and in a trial deployment the later generation was significantly better. UL one-way latencies varied from 1.6 to 2.5 ms. In the DL direction latencies ranged from 1.7 to 2.8 ms. This was a significant improvement over Long Term Evolution (LTE) mobile network in the absolute latency and more significantly in the stability of the latency. The viability of using 5G-URLLC instead of wired connection was proven. A different article explores the benefits of deploying a private network within a small company [18]. Namely the possibility of remote robot control facilitating automation of tedious tasks. Automation can help in reducing the shortage of qualified workers in some industries such as bakers which the paper uses as an example. The 5G Non-Standalone (5G NSA) 3GPP rel.15 network had a RTT of around 10 ms and the robot experienced some movement interruption. The authors believe newer releases should provide better RTT. A showcase study illustrated essential 5G concepts such as Multi-access Edge Computing (MEC) offloading, usage of multiple network technologies and implementation of AI for driving [20]. However, no real data is presented only a presentation of the solution without all the necessary details. A real demonstration of remote driving possibility through the 5G RAN was attempted in different article [40] Furthermore, authors compared the resulting E2E delays with a WiFi solution. 5G performed 3 times better; the average delay was three times lower than what the WiFi connection achieved. However, the experimental results were conducted using the 5G gNB only, no core was involved nor were other users connected to the network. The main added value of the article is in the solution itself. A real car is used and it possesses some awareness with stereo camera system, Global Positioning System (GPS) and other sensors. The car is conceived as a Robot Operating System (ROS) subscriber and the control center is a ROS master. The control center is connected by fibre to the gNB, which provides the wireless connection. Authors conclude that the 5G network is a viable option for remote vehicle control.

5G network provides a solid base for remote control applications. However, it is not a finished solution improvements are needed to ensure resource availability and effective coexistence of remote control traffic with other services within the cell or even UE data streams. This is a problem of resource allocation which we describe in following sections.

4.1.1 Resource allocation problem

It has been shown that above-described methods cannot fulfil the URLLC requirements for a numerous URLLC streams as shown in [41, 42]. Authors devise a solution, built upon lower-layer techniques (fast HARQ + robust MCS), which aims to make URLLC communication massive [37]. The solution is centres around a so-called Massive URLLC Scheduling Technique (MUST) scheduler coupled with network assisted traffic management and QoS-aware congestion avoidance algorithm. Results show an increase in the overall capacity of the whole system close to the upper bound as well as degradation-free URLLC goodput in congested network scenarios [37]. The problem of coexistence of URLLC with other data streams is the case with any MAC channel optimization, therefore it does not have a definite solution. To ensure that the latency constraint of the DL-URLLC traffic is met a multiplexing method called puncturing or pre-emption in which the URLLC traffic is sent over already allocated resources is a standard solution for this problem. In the UL direction the UE uses method called autonomous transmission to transmit URLLC data. The UE is given some predefined resources for the UL transmission in advance, so that the UL random access procedure is bypassed [36]. These solutions create their own set of problems. In the DL puncturing causes decrease in energy efficiency for both the gNB and the UE : the UE that was the destination of the then punctured data receives an interrupted data frame and has to wait for re-transmission. In the UL direction the static scheduling of resources can lead to unused resources and in that way degrading the resource utilization. Therefore, a lot of research effort has been put into finding a way to effectively allocate resources in cells with various service requirements.

4.1.2 State of the art Dynamic Resource Allocation

The research on the topic of effective resource allocation explores alternative methods of resource allocation that are good enough for the wide range of services that the 5G network is set to support. Dynamic resource allocation is the standard allocation procedure present in the mobile network (see Figure 2.3). Presented literature tries to enhance this procedure so that it can be used for allocation of resources for several different types of services.

Article presents simulation results for multi-user URLLC allocation scheme called Dynamic-Point Selection (DPS) and frequency selective multi-user scheduling in the context of DL URLLC enhancement [43]. Furthermore, a resource allocation algorithm is presented that schedules resources for both sub-band and wide-band Channel Quality Indicator (CQI). Both techniques achieve an improvement in latency over standard solutions. In a different study exploration of the usage of Channel-aware Dynamic Resource Block Allocation (CDRA) and Urgency-aware Dynamic Resource Block Allocation (UDRA) in the DL direction is presented [23]. These methods are utilized in conjunction with standard scheduling algorithms to ensure URLLC coexistence with eMBB traffic. CDRA alone performed worse than CDRA with UDRA. UDRA ensures that all URLLC packets for UEs with low CQI are delivered and are not just stacking up in the DL buffer. The simulation results were performed for several packet scheduling algorithms and in each case CDRA + UDRA performed better. Another article proposes a scheduling approach that effectively allocates Dynamic Resource Blocks (D-RBs) eliminating the need for eMBB transmission puncturing [24]. D-RBs are Resource Block (RB)s that are split into smaller parts which are provided to the UEs based on their requirements. Authors implement the D-RBs structure scheduling using conventional schedulers and by introducing a dynamic switching between Round Robin and Best Channel Quality Indicator. Simulations provide promising results for system throughput, UE data rate and spectral efficiency. However, the impact of number of UEs and mobility has not been investigated. Authors of a different article propose a Deep Neural Network (DNN) Channel State Indicator (CSI) approximation and adjust the resource allocation to take the uncertainty of channel estimation into account [44]. The use case considered is vehicular communication, where one Vehicle User Equipment (VUE) requests both eMBB and URLLC slices. with Resource allocation being joint for both slices. The CSI approximating DNN tries to learn the non-linear relationship between the CSI of geographically separated VUEs. CSI is measured only for one of the VUEs in proximity and inferred for the others. The results of the beam-forming loss show that it is not possible to predict all the details of the dynamic channel. This results in increased loss with farther future predictions. However, the CSI overhead is significantly reduced. A review article provides an overview of solutions for Grant Free access with shared and dedicated resources and authors present their solution for Grant Free access [25]. The authors use Deep Reinforcement Learning to select UEs for Grant Free access and assignment of RBs to the selected UEs. Simulation results presented concern only the Deep Reinforcement Learning agent convergence for different amount of UEs and the proportion of them with stable traffic. Different study presents dynamic scheduling procedure for nonspecific traffic pattern [26]. The scheduling is based on two Deep Reinforcement Learning agents: for traffic size and time prediction. The Deep Reinforcement Learning agents use the UEs BSR information history for prediction. The results show that the latency can be reduced to 0.25 ms.

It is important to note that all of the presented solutions are experimental and not yet available in real deployment. In the following sections we investigate other standard solutions currently present in the mobile network.

4.2 QoS

QoS is a higher layer performance management mechanism. It prioritizes packets based on policies for a given type of traffic or specific UE association. It cannot guarantee that resources are going to be available at a given time, it only manages packet arrangement which is not enough for purposes of our solution.

4.3 Slicing

In mobile networks, the communication resources are shared between all connected users, as described in previous sections. However, users (or customers) have different needs, which can be partially met by QoS, but not fully. Also, some users may require a dedicated communication resources, that should be alwayas available to them. Therefore, a concept of slicing has been introduced.

Slicing enables to create a virtual E2E connection providing user tailored service. What should be noted, the reserved resources can still be used by other users if not in use. Despite the all benefits of the slicing, it still has some limitations, such as true E2E connection spanning over multiple networks or Mobile Network Operators (MNOs). The main ethos of slicing is to create an effective E2E resource virtualization and management of the virtual resources so that customer defined parameters are met. Slicing is supposed to become a general automated top down resource management system. This means that in practice resource allocation is done by an algorithm that works with abstracted resources, which implies that the control is not that precise. However, this is not the main reason for opting out of using slicing for our solution. The main issue is the stage in which slicing is available, open RAN implementations are unable to provide E2E slicing options as of now. Creating a truly general solution with the use of slicing is beyond the scope of this work.

Chapter 5

Problem Definition

The aim of this thesis is to optimize the Mobile network parts of the E2E transmission route for Tactile internet applications, i.e., provide low communication delay and reduce communication jitter. 5G RAN has the potential to facilitate data transmission adhering to URLLC parameters [3, 21, 45]. The URLLC transmission parameters are defined as E2E latency below 50 ms, reliability of 99.9999 % and data rate up to 100 Mbps [46]. The standard resource allocation procedures using the recommended network settings (FDD and 30 kHz SCS) provide 3.5 ms and 1.5 ms average delays in UL and DL respectively [3]. In the mobile networks, communication channel quality varies and so does the communication delay. This leads to irregularities in the transmission which are undesirable. Therefore, it is necessary to develop a solution that would reduce the total E2E delay, ensure that the packet deliveries are regular and successful.

5.1 Architecture

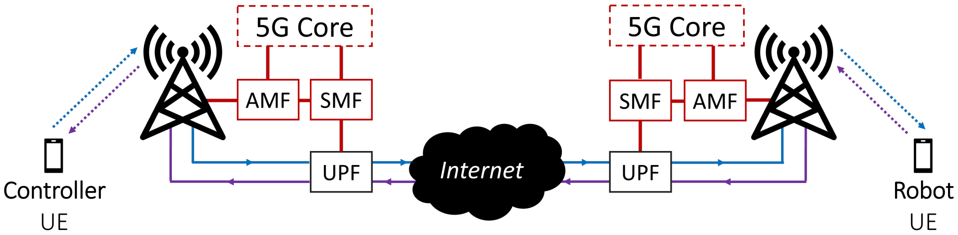

Figure 5.1: Remote Control network architecture. Purple and blue arrows represent data traffic. Red lines represent control plane communication. Controller UE and Robot UE are connected to separate 5G networks separated by the internet. Both UEs can receive and send data at the same time.

The Tactile Internet connection can and will be spanning over multiple (separated) networks, therefore, in this thesis we focus on a case with two independent Mobile Networks, where we have two gNBs interconnected over the Internet. Furthermore, two UEs, representing Controller (human operator who remotely controls a robot) and Robot (the controlled device) are connected to their respective gNB. The gNBs can be located anywhere, there is only the condition which is that the gNBs must be connected.

5.2 Delay and Regularity

Tactile Internet in general assumes the need of control with feedback loop, i.e., control loop that requires human input and the human operator needs feedback. Human operator reacts to a video feed from the robot camera. Humans in general are sensitive to latency between action and reaction of controlled device. This is even more prominent in remote robot control; where for example the robot operator must be able to take action soon enough to avoid hitting objects. Therefore, objective of this thesis is to make the transmission as smooth as possible, mitigate fatigue due to latency and jitter, and make robot control predictable and responsive. Let us define the E2E traffic delay as t^{E2E}:

$$t^{E2E} = t^{UL} + t^{internet} + t^{DL}, \tag{5.1}$$

where t^{UL} is the delay of control UE UL transmission to gNB, $t^{internet}$ is the delay introduced by the internet connection between the gNBs and t^{DL} is the delay robot receiving DL transmission. Smooth robot control in this context means to minimize transmission delay t^{E2E} and also the communication jitter denoted as $var(t^{E2E})$. Jitter represents packet delay irregularity with respect to average over all or moving average over several latest packet delays, i.e., it is a variance of the E2E delay (t^{E2E}). Large jitter values make the control unpredictable because it means that data arrives irregularly. We assume an existing connection between two gNBs has already been optimized, optimization of $t^{internet}$ is out of scope of this thesis, but it could be further extended and optimized. Below we provide an elementary E2E communication latency analysis to cover all the details needed in this thesis. A deeper analysis of the packet transmission delay is described in [3] which goes beyond the needs of this thesis.

Let us start with analysis of loopback delay which is visualised in Figure 5.2. The first delay contributor is the packet processing in the UE. In Figure 5.2 it is illustrated as grey rectangle right next to Ping Start time label. We consider it an inherent device delay and denote it as $t^{UL\ UE\ proc}$. After the packet was processed the UE has to wait to receive wireless resources to start transmitting. In figure Figure 5.2 it is represented by a blue arrow. We denote it is as $t^{UL\ wait}$. $t^{UL\ wait}$ is essentially the time that the packet waits in UE buffer. Therefore, it can be effected by RAN settings and access procedure type. When the UE is granted resources for transmission it transmits the packet for a given time. We denote the time as $t^{UL\ trans}$ and in Figure 5.2 it is shown as a yellow arrow next to $t^{UL\ wait}$. This delay is also effected by RAN settings but also directly depends on allocated resources: their size or BW, their spectral efficiency or channel quality and time allocation spread. By time allocation we mean a time gap between subsequent packet transmissions

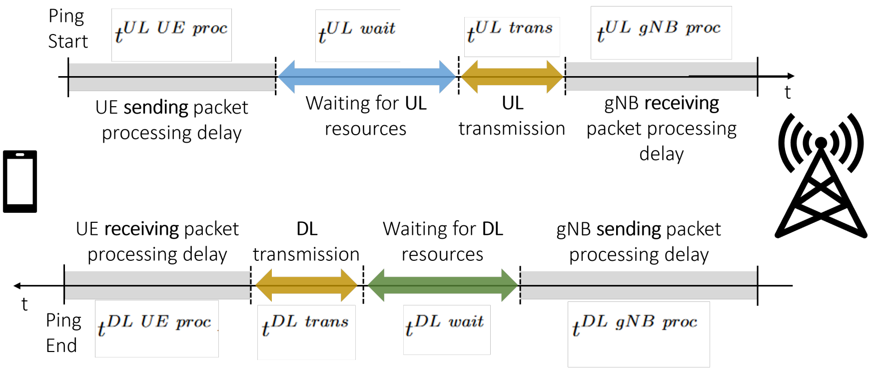

Figure 5.2: Loopback delay adapted from [3]. Gray rectangles signify delays that are inherent to packet sending. Blue and green arrows are delays caused by waiting for resource allocation in UL and DL respectively. Yellow arrows represent delays caused by wireless transmission. Each of the delays visualized in the figure we show associated delay terms which are defined in equations equation (5.2) and equation (5.3). Note that time axis for the DL on the bottom has inverse axis, i.e., starts on right and goes to left, to indicate transmission from gNB to Robot UE.

if the packet transmission could not be sent in one piece. gNB now received the packet but it needs to process it before it is sent back to the UE. Processing delays in after receiving and before sending the packet are denoted as $t^{UL\ gNB\ proc}$ and $t^{DL\ gNB\ proc}$ respectively. As in the case of UE processing delay we consider these delays as an inherent part of network transmission. Both delays are represented by grey rectangles near gNB symbol UL delay on the upper and DL delay on the lower time axis. Similarly to when UE wanted to transmit the packet upstream, packet has to wait for resource allocation in the DL direction. In Figure 5.2 this delay is illustrated as a green arrow and we denote it as $t^{DL\ wait}$. This delay can be effected by RAN settings and access procedure type. When the packet is scheduled for transmission gNB starts transmitting and it transmits for $t^{DL\ trans}$. In Figure 5.2 it is represented by a yellow arrow on the lower time axis. This delay can be effected in the same way as $t^{UL\ trans}$. When the packet is received by UE it needs to be processed before it reaches the program that is waiting for it. We denote this delay as $t^{DL\ UE\ proc}$. In Figure 5.2 it is shown as a grey rectangle near the Ping End mark. We consider this delay fixed.

If we combine all the above described delays we can define t^{UL} and t^{DL} as follows:

$$t^{UL} = t^{UL\ UE\ proc} + t^{UL\ wait} + t^{UL\ trans} + t^{UL\ gNB\ proc} \tag{5.2}$$

$$t^{DL} = t^{DL\ UE\ proc} + t^{DL\ wait} + t^{DL\ trans} + t^{DL\ gNB\ proc} \tag{5.3}$$

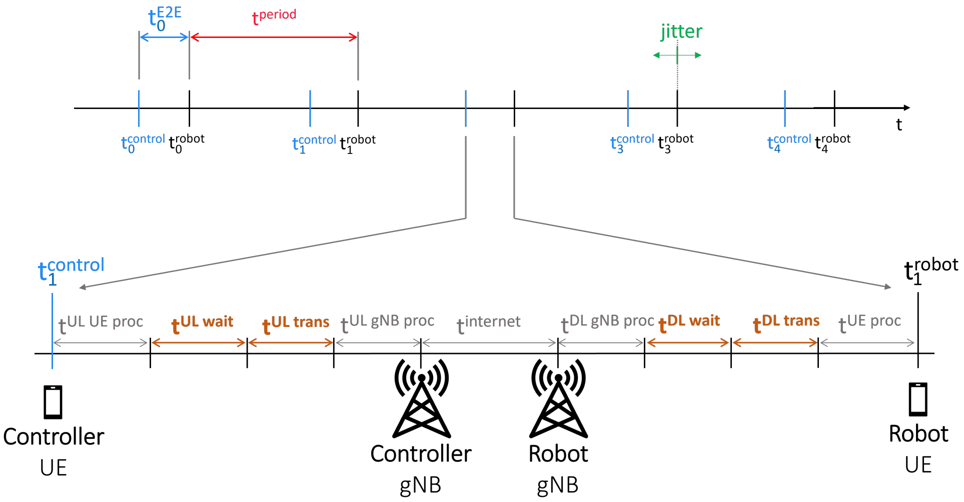

Figure 5.3: Visual definition of t^{E2E} delay. The upper time axis shows periodic traffic and its parameters: t^{E2E}, t^{period} and jitter. On the lower time axis we illustrate t^{E2E} in detail with up-link and down-link components as defined in equation (5.2) and equation (5.3). The delays on the lower time axis highlighted with bold and orange are those delays which we aim to optimize.

In Figure 5.3, we show traffic parameters t^{E2E}, jitter. Furthermore, we see visually described E2E latency in the bottom of the figure with superimposed devices: UEs and gNBs. We assume periodic traffic pattern, which is common for control traffic to both frequently receive status information and keep control link "alive". Therefore, in Figure 5.3 we show t^{period} using red color. The traffic period (and also keep alive period) is t^{period}, and the UE wants to send data in regular intervals following the first transmission. The time instants $(t_i^{control}, t_{i+1}^{control}, \ldots, t_N^{control})$ are the times when the Controller UEsends the control data. Similarly, the time instants $(t_i^{robot}, t_{i+1}^{robot}, \ldots, t_N^{robot})$ are the times when the Robot receives the control data. We expect that the control data from Controller UE are sent repeatedly at regular intervals of t^{period}, i.e., $t_{i+1}^{control} = t_i^{control} + t^{period}$. The data are received at the Robot UE with delay t_i^{E2E}, i.e., $t_i^{robot} = t_i^{control} + t_i^{E2E}$. We can calculate jitter as:

$$jitter = \sqrt{var(t^{E2E})} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(t_i^{E2E} - \bar{t}^{E2E})} \tag{5.4}$$

where $\bar{t}^{E2E}$ is the average E2E delay.

5.3 Reliability

To minimize transmission errors relevant and up to date information about channel quality is necessary. Channel quality information is used to select appropriate MCS in order to achieve given transmission error rate. Then the error rate is monitored in real-time to maintain sufficient spectral efficiency and error rate. However, the gNB has to decide based on approximation of the real channel quality as the CQI report is not up to date rather it is information about the past. Channel measurements can be set to periodic or aperiodic measurements [47]. For the illustration of the problem, let us assume that the measurements are periodic. UE measures reference signal strengths to get Signal-to-Interference-plus-Noise Ratio (SINR) (among others) [47]. Then UE prepares CQI report which is a coarse channel information derived from finer SINR measurements and sends it to gNB regularly to inform the gNB about the current channel quality. After the CQI report arrival the gNB stores the information and chooses MCS index for transmission based on the CQI report. MCS is selected to maximize spectral efficiency of the transmission for the given channel quality, while Block Error Rate (BLER) is kept under pre-defined threshold.

$$BLER = \frac{\text{Number of erroneous blocks}}{\text{TOTAL number of transmitted blocks}} \tag{5.5}$$

However, there is a delay between the arrival of the CQI report and data transmission. The channel changes in remote control traffic may be higher than for standard traffic because of rapid interference pattern changes which may be caused by short Transmission Time Interval used for URLLC [48]. This can lead to unreliable transmissions or resource wasting.

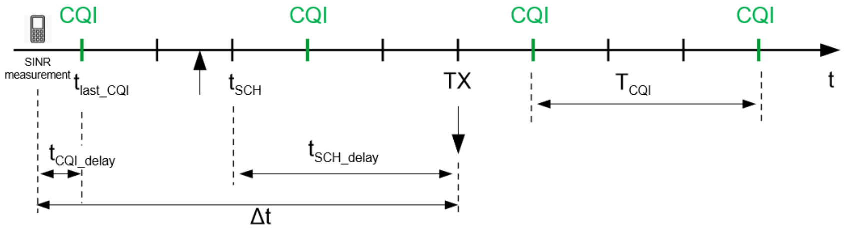

Figure 5.4: This figure illustrates the delay between CQI report reception and data transmission. First **black arrow** represents that some data need to be sent to UE. Second **black arrow** represents transmission of the data. Reproduced from [6].

Let us define Δt as the delay between CQI measurement and data transmission:

$$\Delta t = t^{CQI\_delay} + (t^{SCH} - t^{last\_CQI}) + t^{SCH\_delay}, \tag{5.6}$$

where t^{CQI_delay} is the time from UE SINR measurement until gNB receives the CQI report, t^{SCH} represents the instant when the scheduler schedules data transmission and t^{SCH_delay} is scheduling delay. Then the difference between assumed CQI and real CQI ΔCQI is defined as:

$$\Delta CQI(\Delta t) = CQI(t^{TX}) - CQI(t^{Meas}), \tag{5.7}$$

where $CQI(t^{TX})$ is real CQI that describes the channel state in the instant of the transmission TX in Figure 5.4 and $CQI(t^{Meas})$ is CQI that was used for the data transmission based on a measurement at SINR measurement in Figure 5.4. The higher $\Delta CQI(\Delta t)$ error is than 0 the lower spectral efficiency and resources are wasted. Conversely, the lower $\Delta CQI(\Delta t)$ error is than 0 the higher the probability of erroneous transmission. We quantify transmission errors using BLER parameter.

5.4 Optimizing E2E connectivity

As stated above we need to minimize delay and jitter simultaneously by optimizing the communication resource allocation both gNBs (on Controller and Robot side), considering required data rate and channel quality. The resource optimization needs to be done continually to adapt to the changing channel quality, while looking into the future via channel quality prediction. Therefore, prediction time is denoted as τ. The optimisation task could be mathematically defined as:

$$min(t^{E2E}) \text{ and } jitter \rightarrow 0 \text{ and } BLER \rightarrow 0 \text{ for given throughput} \tag{5.8}$$

Let us delve into each part of equation (5.8) separately.

Minimization of t^{E2E}:

$$min(t^{E2E}) = min(t^{UL} + t^{internet} + t^{DL}), \tag{5.9}$$

we assumed $t^{internet}$ is already optimal therefore:

$$\begin{aligned} min(t^{E2E}) = {} & min(t^{UL} + t^{DL}) + t^{internet} = \\ & = min[(t^{UL\ UE\ proc} + t^{UL\ wait} + t^{UL\ trans} + t^{UL\ gNB\ proc}) + \\ & + (t^{DL\ UE\ proc} + t^{DL\ wait} + t^{DL\ trans} + t^{DL\ gNB\ proc})] + \\ & + t^{internet} \end{aligned} \tag{5.10}$$

Similarly, some other delays are beyond our scope, giving us the final formula for $min(t^{E2E})$:

$$\begin{aligned} min(t^{E2E}) = {} & min(t^{UL} + t^{DL}) + t^{internet} = \\ & = min[(t^{UL\ wait} + t^{UL\ trans}) + (t^{DL\ wait} + t^{DL\ trans})] + \\ & + t^{UL\ UE\ proc} + t^{UL\ gNB\ proc} + t^{internet} + t^{DL\ UE\ proc} + t^{DL\ gNB\ proc} \end{aligned} \tag{5.11}$$

The waiting times t^{wait} reflects the time the data waits in the buffer during PUSCH/Physical Down-link Shared Channel (PDSCH) allocation processes. The transmission length t^{trans} depends on given channel quality, and resource block allocation size and timing.

To get $jitter \rightarrow 0$ we need to ensure that the data transmission is received by the robot at predefined time intervals. If data is sent periodically jitter can vary only of t^{E2E} varies. Then we can restate:

$$jitter \to 0 <=> min(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(t_i^{E2E} - \bar{t}^{E2E})}) \tag{5.12}$$

As we described in $min(t^{E2E})$ part we are focused only on delays caused by mobile network scheduling related delays. The variation of these delay parts depends on given channel quality, and resource block allocation size and timing.

Finally, to get $BLER \to 0$ we need to ensure that MCS is chosen accurately with regards to channel quality.

All of these tasks need to be solved simultaneously within time restriction set up by τ so that the RB allocation in time and frequency domains with correct MCS setting are determined in time for the next transmission instance.

Chapter 6

Proposed Solution

In this chapter, we describe the proposed solution to the problem defined in the previous chapter, i.e., t^{E2E} and jitter minimization in conjunction with error rate minimization. It can be defined as optimization problem with constraints. We have three degrees of freedom: reliability, latency and throughput, which are bound by what can be described as fundamental trade-off which is explored in [49]. For example: if we aim to maximize throughput we must sacrifice reliability because we push for high spectral efficiency by increasing MCS which increases the risk of transmission errors and subsequent re-transmissions cause increased latency. However, if we define constraints, optimization of given parameters is possible under the condition that channel is not degraded beyond a point where no solution is possible.

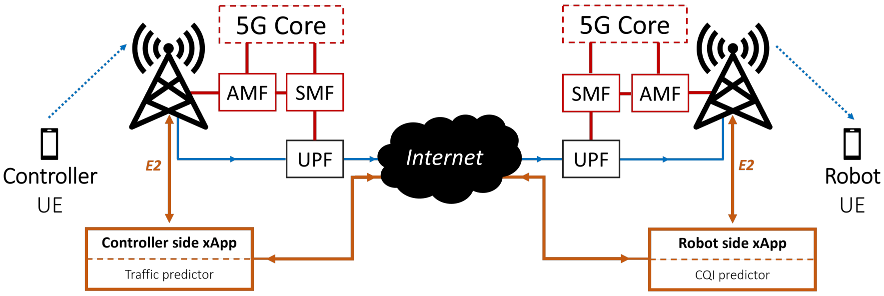

Figure 6.1: Architecture of the proposed solution, focusing on unidirectional (control) with the proposed xApps.

In our solution we consider only one-way E2E traffic. If we assume that the UE HW setup allows transmission in both UL and DL directions simultaneously then UL transmission is not interfering with the DL transmission and vice versa. Therefore, we can assume that solutions for given optimization task in both directions are independent thus we consider only one-way E2E traffic in to find an optimal solution. Note that same principle for one direction can be exploited for the other direction, but to simplify the design we focus only on one direction.

In robot control traffic there often is a pattern which can be used to improve performance of relevant transmission characteristics. Therefore, the proposed solution is built on an assumption that the control data traffic is being send periodically. Generally, the packet size can vary from one transmission to another. Furthermore, the traffic requirements are more sensitive to channel quality can change because of the latency requirement coupled with guaranteed throughput. We want to reach E2E URLLC parameters: erroneous packet rate below 10^{-5}, E2E packet delay below 50 ms and throughput up to 100 Mbps. To provide such a service, resource allocation must be done pro-actively and coordinated among both gNBs. We rely on predictors to help us allocate resources ahead of time. Concretely, it is a traffic pattern predictor that predicts time and size of the next transmission and CQI predictor which predicts channel state in the next transmission. However, prediction scheme design for CQI, UL traffic pattern and corresponding packet data sizes are beyond the scope of this work. Therefore, we use predictors designed and presented in literature.

Traffic pattern information can be explicitly provided by the Controller or it could be estimated by pattern recognition algorithms in both time regularity and data size as presented in [26]. To guarantee given BLER and not waste resources due to low spectral efficiency our solution employs Hidden Markov Model based DL transmission CQI predictor presented in [48]. Both of these predictors need to be trained and for that data is needed. We present a solution that uses O-RAN RIC controller to gain access to relevant RAN parameters with minimal latency in a way that does not slow down gNB processes. RAN information collection is presented in more detail in section 6.2.

The O-RAN RIC architecture presented in section 2.4 provides a framework for development of third party control application called xApp. xApp can leverage the provided near real-time interface to control and monitor RAN functions. Our solution implements two xApps, one at Controller side gNB and one at Robot side gNB. Each has its set of responsibilities to ensure that the traffic requirements are met. Full description of xApp responsibilities and functionality is presented in section 6.1

The xApps share traffic information to coordinate pro-active resource allocation at both gNBs. Once xApp on Controller's side allocates resources for a future transmission (assuming that the allocation corresponds with traffic pattern thus data is transmitted in that transmission) we know when and how big is data that is going to be transmitted. If we then share this information with Robot side xApp we can eliminate ambiguity about incoming traffic and allocate resources beforehand. Therfore, coordination could help stabilize traffic flow and minimize packet jitter that can be introduced by gNB interconnection and delay caused by waiting for DL grant. More information about xApp communication can be found in section 6.3.

6.1 Description of xApps

In this section we describe functionality and design of xApps. Part of xApp design is shared for both Controller and Robot side xApps. The common design parts are described in section 6.1.1. Then we delve into specifics of Controller side and Robot side xApp in section 6.1.2 and section 6.1.3 respectively.

6.1.1 xApp states

The xApp has these three states which define general behavior of xApp programs:

1. **Waiting for E2E request** - in this state xApp waits, when request comes connection is established and UE presence in the cell is verified.
2. **Learning** - in this state data are fed into predictor so that it can predict future events.
3. **Control and Evaluate** - in this state resources are allocated based on available traffic information and the allocations are scrutinized.

The first (default) state **Waiting for E2E request**, is an idle state. Controller xApp waits for E2E establishment request from the UE which is then forwards to Robot side xApp. When the UEsends E2E request to the Controller side xApp connection over Transmission Control Protocol (TCP) socket with Robot side xApp is established. Controller side xApp sends keep-alive messages to maintain the TCP connection. If the connection was established successfully xApps change state to **Learning**.

6.1.2 Controller side xApp

If UE has specified periodic traffic pattern explicitly the Controller xApp skips the Learning state. Otherwise, the Controller UE starts transmitting and the gNB will use Dynamic Scheduling for resource allocation, while the xApp provides relevant parameters to traffic predictor. Traffic predictor needs the following data: BSR and information about when Scheduling Request arrived. Learning state program interactions are visualized in Figure 6.2 using green arrows: data is collected from RAN and traffic predictor accesses it to learn the pattern.

When traffic predictor converges which means that the predictions are not improving with new data anymore, the Controller xApp changes state to **Control and Evaluate**. The main responsibilities in this state are to schedule resources according to traffic predictor output, send traffic information to Robot side xApp and evaluate the current allocation scheme. Figure 6.2 visualizes interaction of program parts by blue arrows. For resource scheduling we use Configured Grant technique which eliminates Scheduling Request and

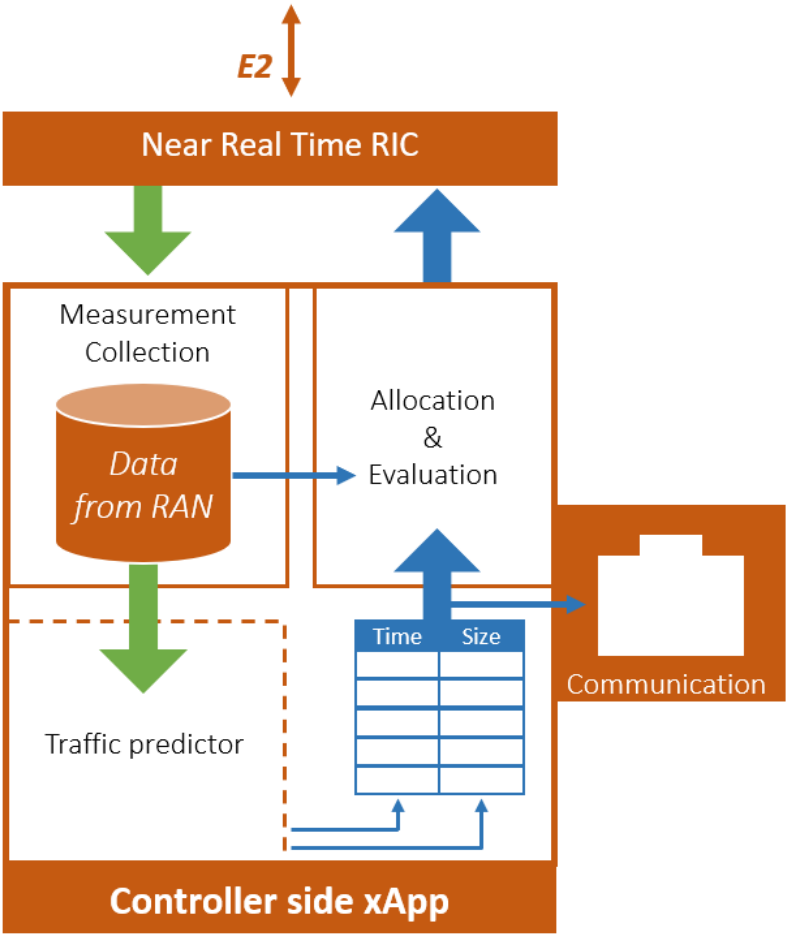

Figure 6.2: This figure illustrates Controller side xApp program parts. Furthermore, the colored arrows represent activity in Learning, and Control and Evaluate states. Learning state interactions are shown by green arrows. Control and Evaluate state program interaction is shown by blue arrows. In this state the time-size pairs are generated and stored in the FIFO queue.

BSR delays, and relies solely on prediction as described in [26]. If traffic predictor is used (Controller UE has not declared traffic pattern explicitly) the following applies. Traffic predictor provides time instant and data size of next data transmission. However, the prediction is not instant; it takes time (0.6 ms on average) to generate the required information [26]. To overcome this issue we can generate series of future Controller UE transmissions one by one. Then the generated future transmission time-size pairs stored in a traffic information First In First Out (FIFO) queue. Time-size pairs in the queue are transformed into PRB grants one by one in time smaller than τ to adhere to chapter 5. The PRB grants are calculated with regards to minimizing waiting delay and transmission time using MCS that ensures required BLER constraint. This means that resources are scheduled at a time that was predicted and frequency allocation is maximized to lower transmission time. Furthermore, traffic information is sent to Robot side xApp regularly. The list of future Controller transmissions shared with Robot side xApp has to be sufficiently long and sent with long enough time reserve so that Robot side xApp has enough time to apply the information. In case of purely periodic traffic RB grants are added into circular FIFO queue directly as traffic predictor is not needed and the same pattern repeats itself indefinitely. The traffic pattern is then shared with Robot xApp only once.

To *evaluate* the effectiveness of the whole allocation scheme we track if Scheduling Request was not received which would indicate small allocation size or allocation at an incorrect time instant. If scheduling request was received we also need the following BSR value to get information about data size that needs to be transmitted. Then a corrective action can be issued based on this information. Furthermore, a difference between (total) allocated data size and the data size that was sent to the Robot UE needs to be monitored. If the cumulative difference between the UL Controller UE allocations and data the gNB sent to Robot UE has an increasing trend corrective action is taken to decrease predicted data sizes by an offset. By monitoring all of these parameters we can make sure that the allocation works as it should.

To verify that the transmission is reliable we also monitor the transmission error rate. We use a cautious approach to MCS selection: when error rate increases above threshold stricter than requirements that need to be ensured MCS is lowered. However, when the channel conditions are too poor to transmit specified data volumes at lowered MCS the end message is sent to Robot xApp and QoS parameters are set in RAN according to required transmission parameters.

6.1.3 Robot side xApp

In the Robot side xApp the traffic flows in DL direction and CQI predictor is used for helping in MCS selection. The CQI predictor needs CQI data for learning which are provided by the xApp. However, when the CQI predictor finishes the learning stage the Robot side xApp does not immediately change its state to Control and Evaluate. Robot side xApp has to wait for traffic information from Controller side UE before it can start the allocation process. The Learning state program interaction is shown in Figure 6.3 using green arrows.

When first traffic information message from Controller xApp is received, Robot xApp changes state to **Control and Evaluate**. The main responsibilities in this state are to schedule resources according to received traffic information and predicted CQI, and evaluate the current allocation scheme. Figure 6.3 visualizes interaction between program parts in the Control and Evaluate state as blue arrows. To *allocate resources* according to traffic information received from Controller xApp we need to get information about when the first packet arrives to Robot side gNB DL buffer. For that we can monitor the DL buffer occupancy for first packet arrival. Then start allocating from that moment according to the shared traffic information. The allocation is to be done in conjunction with CQI predictor as presented in [48]. The CQI predictor provides CQI estimation of the real channel state that is closer to reality than standard estimation and thus helps us exploit nearly full channel capacity and mitigate repeated transmissions [48]. Evaluation of the traffic allocation is based on simultaneous tracking of DL buffer occupancy and sum of transmitted data. Ideally, data would not wait in the DL buffer at all and the sum of received data would be equal to the sum of Robot UE allocations. In other words, resources would be scheduled just in time for transmission and the allocation size would be precisely equal to the data size that needs to be transmitted. If the cumulative difference between the DL Robot UE allocations and data the gNB received over internet has an increasing trend corrective action is taken to decrease predicted data sizes by an offset.

For the remote control traffic it is very important to track jitter, delay and reliability of the transmission. To ensure that jitter is minimized the data needs to be received at the Robot UE with the same intervals between transmissions. This should be taken care of at both the Controller gNB and the Robot gNB. However, the two gNBs are connected through the internet which is by definition best effort and that can create additional jitter, delay and lost packets. To mitigate some of the delay variation (jitter) that can be caused by the internet we can sacrifice a few ms in total E2E delay for jitter minimization. When jitter would reach certain threshold value, which would cause that resources scheduled for Robot UE are unused, then time of future transmissions would be delayed by an offset. However, if the internet connection becomes inadequate in terms of jitter end message is sent to Controller xApp and QoS parameters are set in RAN according to the information that Robot xApp has.

Evaluation of the MCS chosen based on the CQI predictor is done by tracking wireless transmission error rates. If error rate reaches given threshold MCS is lowered so that the error rate is mitigated. However, if theMCS becomes too low to transmit specified data volumes the end message is sent to Controller xApp and QoS parameters are set in RAN according to the information that Robot xApp has.

6.2 Measurement Collection

The Near-RT RIC can access any of the exposed RAN functions and their parameters that have been implemented in any E2 Service Model. This way measurements or parameter values can be collected periodically with period of 1 ms or larger. In the Controller side xApp we need we need to gather relevant parameter values to learn the traffic predictor, for PRB grant calculation and evaluation of the scheme. For the training of the traffic pattern predictor we need BSR and information on when Scheduling Request arrived [26]. The training occurs while the UE uses Dynamic UL scheduling procedure (illustrated in Figure 2.3). After the training is completed no further data collection for traffic predictor is necessary. To calculate PRB grants for Controller UE we need current MCS. In the evaluation state, parameters that could be used for traffic prediction evaluation are the Data Radio Bearer (DRB) statistics which include the total amount of data that has been sent through a given DRB and transmission error rates. Furthermore, if any Scheduling Request occurs it is provided to the Controller side xApp with subsequent the BSR value Controller UE has sent.

In the Robot side xApp we need we need to gather relevant parameter values for CQI predictor and evaluation of the scheme. The channel predictor we chose predicts CQI and requires past CQI values so that is can predict the next CQI [48]. Therefore, Robot xApp extracts the required CQI parameters and provides them to the predictor while learning and inferring [48]. To estimate the transmission start we use DL Buffer occupancy value. In the evaluation state, parameters that could be used for traffic allocation evaluation are the DRB statistics which include the total amount of data that has been sent through a given DRB and transmission error rates.

6.3 Protocol

This section describes communication between proposed solution parts: Controller UE with neighboring xApp, Controller xApp with Robot xApp. Firstly let us describe communication between Controller UE and its neighboring xApp. The UE that wants to be Control source of E2E data stream needs to notify the UL xApp that the E2E connection should be set up. This could be solved using mobile network control signalling but for simplicity let us assume that the UE has the ability to connect to the xApp through TCP socket directly. Controller UE sends its neighboring xApp a message that contains either requested traffic pattern, start of the transmission and size of the required allocation or just request for Remote Control traffic. After receiving the message Controller xApp confirms that the message has been received. Then tries to establish connection with Robot xApp, then informs the UE about the outcome.

Resource allocation information has to be shared with Robot side xApp. The information sharing has to be reliable and effective to mitigate resource wasting. Therefore TCP socket connection is established between the xApps. The data size that is sent over the TCP socket should be minimal to not put additional strain on the gNB internet connection. Therefore, the messages need to be designed with this in mind.

There could be several types of messages based on the information that they carry: initial message, keep-alive message, traffic information message, and end message. **Initial message** serves to establish the communication between the xApps and exchange information about UEs. The Controller side xApp sends a message to the Robot side xApp with Robot UE identifier. If the chosen Robot UE is connected in the chosen Robot gNB cell request confirmation is sent to Controller xApp. **Keep-alive message** is just a small packet sent at given intervals with some random data to sustain the connection. After Robot xApp receives the message it sends it back to Controller xApp. This way both xApps know that the connection is working. **Traffic information message** contains one of the following:

1. information about traffic pattern (in the case of purely periodic traffic)
2. information about several future Controller UE traffic predictions

In the case Controller UE declared periodic traffic pattern the first option applies. Otherwise, (when traffic predictor is used) the second option applies. In this case a list containing a certain amount of time-size predicted pairs is sent to Robot side xApp. It should contain only *future* time-size pairs. The list should be long enough so that Robot xApp has enough traffic information for allocating resources to the Robot UE until next traffic information arrives. The Controller xApp sends this message when the transmission starts and then at regular intervals. The Robot xApp always has to send confirmation that the traffic information message has been received and specified traffic pattern is possible on its end. If the transmission is not possible the end message is sent. **End message** can be sent by either xApp to terminate the connection. After termination of xApp connection QoSparameters are set on both ends. Essentially, the xApp gives up and hands over the responsibility to to deliver specified transmission requirements to the network.

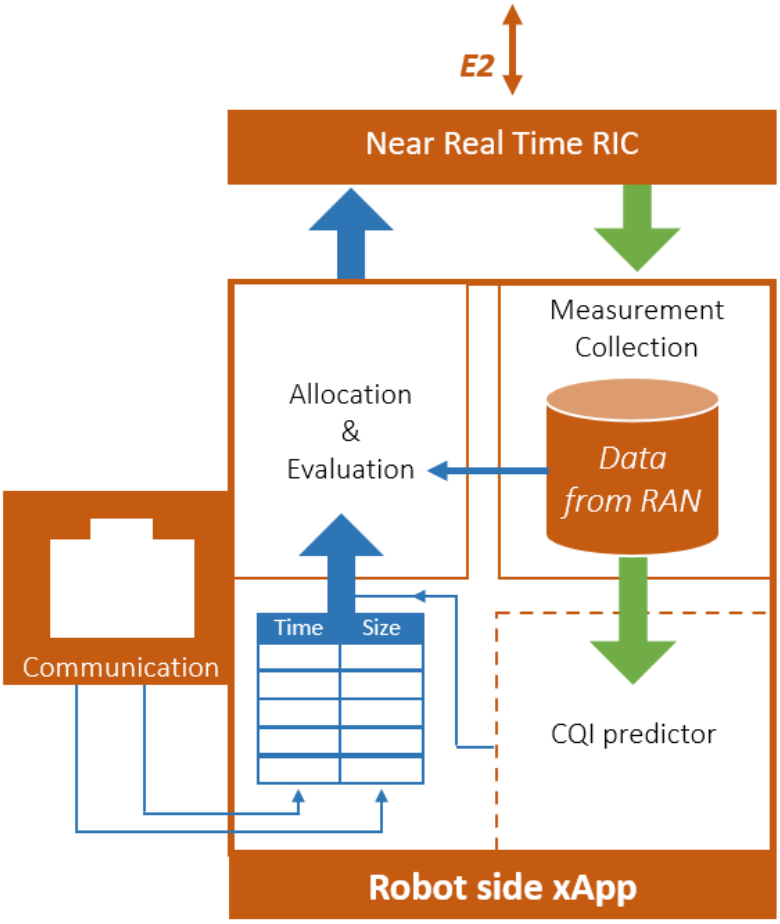

Figure 6.3: This figure illustrates Robot side xApp program parts. Furthermore, the colored arrows represent activity in Learning and, Control and Evaluate states. Learning state program interaction is shown using green arrows: data is collected from RAN and CQI predictor accesses it to be able to predict CQI. Control and Evaluate state program interaction is shown by blue arrows. FIFO queue data is used for allocation whereas, data from RAN is accessed to evaluate allocation.

Chapter 7

Implementation

In this chapter we present implementation that using O-RAN compliant 5G network (RAN + Core) implementation called OpenAirInterface. The purpose of the implemented xApps is to test the fundamental concept of the proposed solution. We need to test that Near Real-Time RIC is fast enough to allocate resources. We need to test that sharing traffic information is a better solution then simply predicting traffic at both ends. And to test that controlling grants at both ends can stabilize traffic.

First we present OpenAirInterface (OAI) and their Near real time RIC implementation FlexRIC section 7.1. In section 7.2 we present the implemented solution architecture and then its parts.

7.1 OAI

OpenAirInterface is an open-source software implementation of the 5G network. It aims to create an open cellular ecosystem so that the research and development and the deployment costs of the network are minimized. The deployment costs are minimized because OAI can run on any Commercial Off-The-Shelf (COTS) hardware, no special hardware is necessary to run the OAI SW [50]. OAI Software Alliance (OSA) is the entity that supports the development efforts and elicits the adoption of OAI [51]. It is a non-profit organization founded by EURECOM - a prominent French graduate school and research center and is now supported by a wide range of commercial institutions from the industry [52]. There are four main projects within the OAI each focusing on a different aspect of the SW implementation 5G network stack: 5G-RAN, 5G Core Network, Operations and Maintenance (OAM) and Continuous Integration / Continuous Deployment (CI/CD). OAI Radio Access Network (OAI RAN) implements the full gNB stack in the Standalone or Non-Standalone versions and with or without a functional Centralized Unit/Distributed Unit (CU/DU) split [53]. The main aim of the 5G Core Network project is to provide the full 5G core functionality on a COTS HW. Every network function that is implemented can be run on one of the deployment platforms: Bare-metal installation (or in virtual machines), in Docker containers and Cloud-native deployment using Helm Chart (on

OpenShift/Kubernetes cluster) [54]. Operations and Maintenance project addresses the control and deployment of the network from the service-based perspective. It aims to do so by implementing FlexRIC, Xapp Software Development Kit (SDK) and Multi-access Edge Computing Platforms (MEP) [55]. FlexRIC is a RAN Intelligent controller which provides control and monitoring of various RAN functions and parameters. Developers can use the Xapp SDK to develop applications that interact with the RAN nodes over the interface provided by FlexRIC. MEP are the last part of the OAM project group. It serves as integration layer for development of user-tailored network services. The fourth and final project is the CI/CD which is in the hands of the DevOps team. The DevOps make sure that the testing is automated, the documentation is Up-to-Date and support the development teams in general [56].

7.1.1 FlexRIC

FlexRIC is a RIC implementation by the OpenAir Software Alliance. The main goals of the team were to create a RIC controller flexible enough to work with any RAN implementation and efficient enough to run several xApps concurrently.

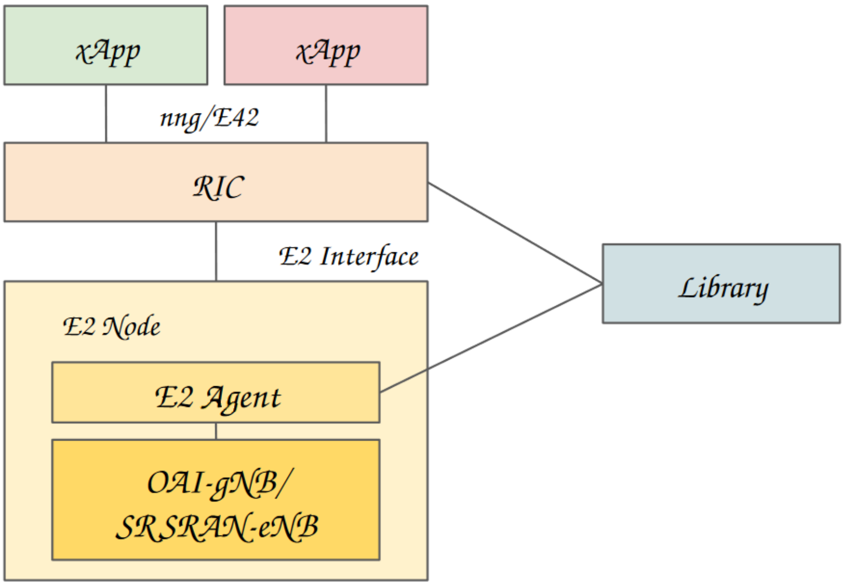

Figure 7.1: FlexRIC architecture reproduced from [7]. Shows FlexRIC architecture parts.

7.2 The fundamental concept

In this section, we describe the implementation of the proposed solution. We abridged the solution described chapter 6 to test the system design concept is viability. The following needs to be verified to prove that the design concept is sound:

1. Near Real-Time RIC is fast enough to allocate resources
2. Near Real-Time RIC is stable enough to support critical traffic
3. Sharing of traffic information is more reliable than traffic prediction
4. The system is able to minimize delay and jitter

To test that these are true we can use purely periodic traffic which will be declared by Controller UE at the beginning of the transmission. Therefore, we do not need traffic prediction and we are not interested in reliability evaluation either thus CQI prediction is not needed. The main focus of the implementation is to prove that FlexRIC implementation and its Software Development Kit can be used to develop an xApp to allocate resources at the specified time and that our design concept is sound.

7.2.1 Architecture

We are using the same network structure as described in chapter 6:Proposed Solution: two gNBs and two UEs each connected to one gNB. gNBs are separated by internet which causes delay and jitter. We use four programs one at each of the nodes where each has a different purpose:

1. node - Controller UE generates data and sends traffic information to its neighboring xApp running near node 2.
2. node - Controller side gNB hosts an xApp that receives traffic information from Controller UE , allocates uplink resources and shares traffic information with xApp running at node 3.
3. node - Robot side gNB hosts an xApp receives traffic information from Controller side xApp and allocated downlink resources.
4. node - Robot UE receives data sent by Controller UE and evaluates the delay of each packet.

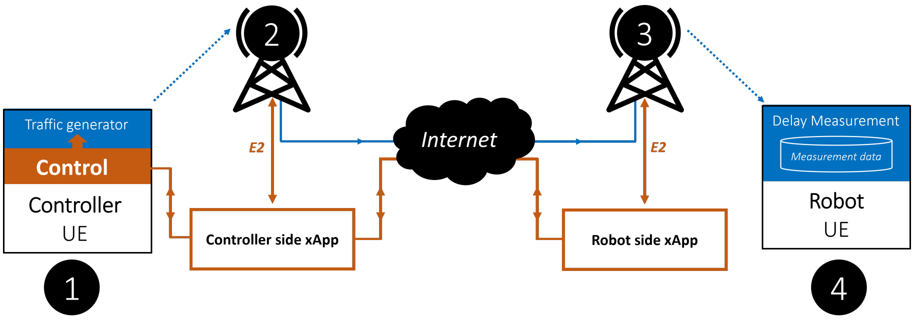

Figure 7.2: High level architecture with node numbers and their associated programs. The blue arrows represent user data flows and the orange arrows represent xApp data control flows.

Let us describe data flows which are represented by blue arrows in Figure 7.2. User data travels from Controller UE through the wireless link to the gNB. Controller side gNB uses UPF to forward the traffic through the internet to the UPF at the Robot UE side. Robot side UPF pipes the user data to its gNB which in turn uses the wireless connection to send the data to its destination: Robot UE . Orange arrows in Figure 7.2 represent control data flows which are described below. The control data flows are described below. Controller UE establishes TCP connection with the neighboring xApp then sends E2E connection request which is the initial message type. Then Controller UE waits for confirmation that the connection between Controller xApp and Robot xApp was established so that periodic traffic pattern information could be shared. After E2E connection request (initial message) is received, Controller side xApp tries to establish connection with Robot side xApp. If the connection between xApps is established Controller side xApp sends connection establishment confirmation to Controller UE which in turn sends its periodic traffic pattern in traffic information message. Finally, the traffic pattern that Controller side xApp received is shared over the TCP connection with Robot side xApp using traffic information message and confirmation of message delivery from Robot side xApp is awaited. After confirmation reaches Controller side xApp it sends confirmation to Controller UE . This starts traffic generation in the Controller UE. Then Controller UE sends keep-alive messages to its neighboring xApp. The Controller UE program can also send end message which terminates all the control programs.

In the following subsections we take a closer look at each of the four programs both in terms of function and design.

Node 1) Controller UE

The Controller UE is user data source node as well as E2E connection initiator and terminator. As the only node of the four it creates both control and user data in their respective program parts. The control part of the program has two modules: module for communication with neighboring xApp and command line interface module. Communication module is responsible for communication with xApp according protocol specified in section 6.3. It sends Initial message, Keep-alive messages, Traffic information message and End message. Command line interface module instructs the other program parts what to do. It sends command to initiate and terminate E2E connection, and the operator can specify parameters of generated traffic. Generated traffic can be either use UDP or TCP connection, it is strictly periodic with constant packet size. When the user specifies traffic type, packet period and packet size through the command line interface, the settings are passed on to the traffic generator. Traffic generator creates "user" data using these parameters after it is instructed to do so. Each packet contains timestamp and padding to comply with the chosen size. The timestamp is then used to measure E2E delay. We can summarize the functions of Controller UE program is the following manner:

- Control sets traffic parameters for DELAY MEAS and also sends these parameters to the Controller side xApp
- Traffic generator creates traffic which not only adheres to the parameters enforced by the Control part but also contains a time stamp that is used in delay measurement.

Node 2) Controller side xApp

Controller side xApp shares traffic information with Robot side xApp, collects data from RAN and allocates resources for Controller UE . We consider only periodic traffic, therefore traffic information is shared only in the beginning of the transmission. To maintain communication keep-alive messages are sent to the Robot Side xApp. For resource allocation we need information from RAN, we describe details about what information is needed in section 7.2.2. Resource allocation itself consists of two parts: calculation of resources necessary and repeated allocation. As the traffic is uniform in both time and size the calculation is performed only once and then the same resource allocation is repeated at given intervals. The function of the Controller side xApp is summarized below:

- Receive control messages from Controller UE.
- Processes messages:
  - Save received traffic information
  - Send traffic information Robot side xApp
  - Send keep-alive messages
- Use saved traffic information to calculate allocation size
- Repeatedly allocate resources for Controller UE

However, the concurrent operation of several sockets with a control loop is not the biggest issue of the development process. It is the amount of parameters that would have to be set to configure the configured grant. Finding the correct definition in the standards that was cumbersome and ambiguous at times. Therefore, the parameters that were used are attached in the appendix for the reader's convenience.

Node 3) Robot side xApp

The last of the control programs - Robot side xApp - runs near gNB that serves Robot UE . Robot side xApp receives traffic information from Controller side xApp, collects RAN information and allocates resources to Controller UE . As periodic traffic is considered only one traffic information message is expected. To maintain communication upon reception of keep-alive message Robot side xApp responds with another one. Accurate resource allocation necessitates information from RAN, we describe details both about setting of parameters and necessary information in section 7.2.3. Resource allocation itself consists of two parts: calculation of allocation size and repeated allocation. As the traffic is uniform in both time and size the calculation is performed only once and then the resource allocation is repeated at given intervals. The function of the Robot side xApp is summarized below:

- Receive control messages from Controller side xApp.
- Process messages:
    - Save received traffic information
    - Reply to keep-alive
- Use saved traffic information to calculate allocation size
- Repeatedly allocate resources for Robot UE

Complication in this control design lies in the inflexibility and ambiguity of the standard SPS. Inflexibility in terms of periodicity setting, which is defined as a list of given intervals. Furthermore, the TS standard defines that the first occurrence and size of the DL resources is solely determined by the DL scheduler. Therefore, design ideas need to be tested on real gNB node.

Node 4) Robot UE

Robot UE is the fourth and final node. Its function is to receive generated data then calculate delay and jitter of the received traffic. Results are saved in a file for later analysis. The delay measurement uses timestamps embedded in packets to calculate delay and jitter. If the measurement is to be trustworthy time synchronization between Controller UE and Robot UE is necessary because we rely on timestamp difference for delay calculation. This is possible only because of the test architecture described in section 7.2.1. Both

Control UE and Robot UE are run on virtual machines within the same local network. Therefore system time synchronization is possible using Precision Time Protocol (PTP). Authors in [39] used program called PTP daemon that implements PTP. The same program could be used to synchronize our programs.

7.2.2 Detailed look at Configured Uplink Grant setting

Configured Grant is a standard scheduling procedure and is exposed over RAN Control E2 Service Model. This procedure allows us to allocate resources without a prior Scheduling Request from UE as it is the case in Dynamic Scheduling procedure. However, list of Configured Grant parameters (see Appendix table 9.5) need to be set accurately in order to decrease delay. From all the required parameters only few are important for implementation in the defined scope. We need to allocate resources in frequency and time domains and set when the transmission should start.

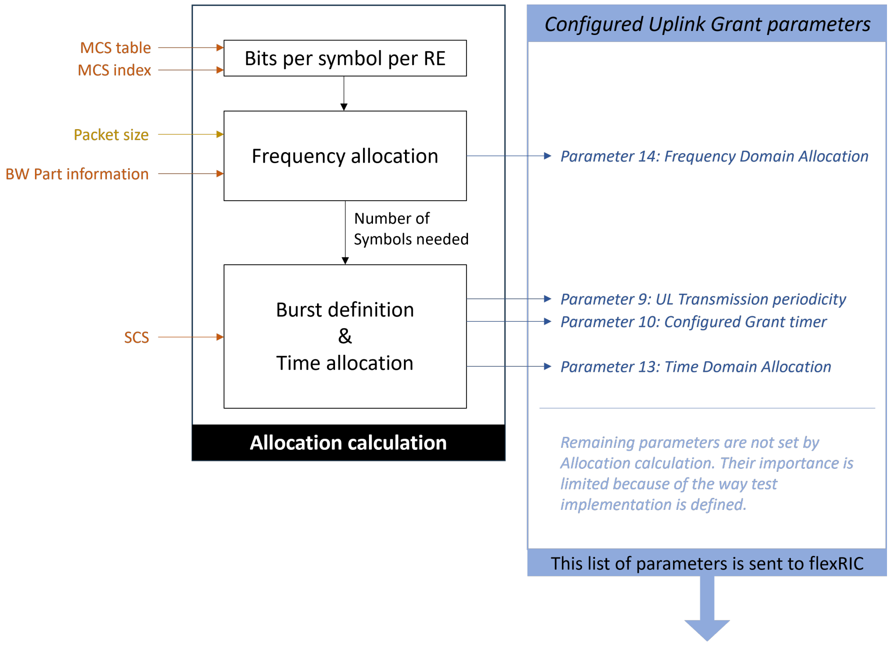

Figure 7.3: This figure describes calculation of frequency and time allocation. The allocation calculation also defines transmission burst that the UE should use. By transmission burst we mean fast consequent transmissions of small amount of data. The orange and yellow arrows signify required input information and the blue arrows represent calculated output that set related Configured Uplink Grant parameters. Whole parameter table can be found in Appendix table 9.5.

For allocation of resources we chose Configured Uplink Grant Type 2 procedure because it is defined as a part of RAN Control E2SM standard and allows us to control allocation precisely on both frequency and time. Configured Uplink Grant Type 2 has 16 available parameter values out of which 11 are mandatory as described in Appendix table 9.5. Let us describe the process of assigning parameters that are crucial for resource allocation: Frequency Domain Allocation, UL transmission periodicity, Configured Grant Timer and Time Domain Allocation. These parameters define the uplink transmission and have to be chosen in a coordinated way that is shown in Figure 7.3. We call it allocation calculation and it chooses frequency allocation, time allocation and burst definition. Burst is a set of consequent transmissions carrying small amount of data each. The first step in allocation calculation is computation the amount of data one symbol with BW equal to one RE can carry. For this we need used MCS table and MCS index that were chosen for the transmission. In the second step frequency allocation is determined. The BW allocated to Controller UE should be maximized so that the transmission time is minimal. The frequency allocation computation needs to know packet size, Controller UE BW part information and the output of the previous step - bits per symbol per RE. Output of this step is parameter Frequency Domain Allocation value and number of symbols which is necessary to transmit full packet size. The last step defines the burst transmission and time allocation. It takes in two values SCS and output of the previous step: number of symbols necessary to transmit full packet size. Burst is defined by two parameters: UL Transmission Periodicity and Configured Grant Timer. UL Transmission Periodicity specifies time interval between transmissions in the burst (details in Appendix section 9.3.6). Whereas, Configured Grant Timer defines how many of those small transmissions are in the burst (details in Appendix section 9.3.7). Finally, Time Domain Allocation parameter (details in Appendix section 9.3.10) is defined so that the there are enough resources to transmit the whole packet. Another important parameter is the Time Domain Offset which defines when exactly should UEstart transmitting (details in Appendix section 9.3.9). Other parameters are chosen according to previous RAN setting. When all the mandatory parameters have been selected we need to send the parameters to FlexRIC so that it creates Configured Uplink Grant in gNB. The messages that are to be sent to set up the Configured Uplink Grant are described below. Configured Uplink Grant can be configured using the Control Service style within the standard RAN control E2SM [9]. The O-RAN RAN Control E2SM standard defines information structures of several formats to carry requests to RIC. To create Configured Uplink Grant within Control Service Style control Header Format 1 and control Message Format 1 are defined in Appendix table 9.1 and Appendix table 9.2 respectively.

E2SM-RC Header Format 1. This header format has 3 mandatory information elements:

1. UE identifier
2. RIC Style Type
3. Control Action ID

UE identifier is a data structure that contains information about the UE . Such as associated RAN station type (gNB-monolithic, gNB-CU, eNB, ...), UE identification number or PLMN code. **RIC Style Type** is defines the Service Style Type to be used. In the case of Control Service style the element should be set to 2 which according to the Appendix table 9.3 selects Radio Resource Allocation. **Control Action ID** identifies a specific action that is available within the chosen Service Style Type. Radio Resource Allocation Style Type has 6 actions. To select Configured Grant Control Action number 4 should be chosen as per Appendix table 9.4. By setting this element the Header is filled and we can fill the message.

E2SM-RC Message Format 1. The E2SM RAN Control message Format 1 contains a list of concrete RAN parameters to be effected. Structure of this Message Format is defined in Appendix table 9.2. Every parameter is defined by its parameter ID and value type (which contains the parameter value). All RAN parameters relevant for Configured Grant Control are shown in Appendix table 9.5. These parameters enable complete control over start of the grant, its allocation and modulation index etc.

7.2.3 Detailed look at Semi-Persistent Scheduling setting

Semi-Persistent Scheduling is a standard down-link scheduling procedure and is exposed over RAN Control E2 Service Model. This procedure allows us to allocate resources to UE periodically. However, it does not allow to choose precise allocation size or start of the transmission. Semi-Persistent Scheduling allocates resources for DL transmission for a given UE after data is registered in gNB DL buffer intended for the UE. Allocation of the first transmission is repeated at given periodicity and completely taken care of by the network [57]. Ideally, we need more precise control which ensures exact allocation of resources in time and frequency domains for the implementation to be more general. However, controlling just periodicity is enough to test the design concept. Furthermore, we can create traffic with one of the periodicity values that parameter Semi-Persistent Scheduling (SPS) Periodicity allows us to set (more details Appendix table 9.11 and Appendix section 9.4.1). We can control generated traffic periodicity which could be chosen to adhere to one of SPS Periodicity values as declared in Appendix table 9.11.

The messages that must be sent to set up Semi-Persistent Scheduling are described below. Semi-Persistent Scheduling can be configured using the Control Service style within the standard RAN control E2SM [9]. The O-RAN RAN Control E2SM standard defines information structures of several formats to carry requests to RIC. To create Semi-Persistent Scheduling within Control Service Style control Header Format 1 and control Message Format 1 are defined in Appendix table 9.1 and Appendix table 9.2 respectively.

E2SM-RC Header Format 1. This header format has 3 mandatory information elements:

1. UE identifier
2. RIC Style Type

3. Control Action ID

UE identifier is a data structure that contains information about the UE . Such as associated RAN station type (gNB-monolithic, gNB-CU, eNB, ...), UE identification number or PLMN code. **RIC Style Type** is defines the Service Style Type to be used. In the case of Control Service style the element should be set to 2 which according to the Appendix table 9.3 selects Radio Resource Allocation. **Control Action ID** identifies a specific action that is available within the chosen Service Style Type. Radio Resource Allocation Style Type has 6 actions. To select Configured Grant Control Action number 3 should be chosen as per Appendix table 9.4. By setting these elements the Header is filled and we can fill the message.

E2SM-RC Message Format 1. The E2SM RAN Control message Format 1 contains a list of concrete RAN parameters to be effected. Structure of this Message Format is defined in Appendix table 9.2. Every parameter is defined by its parameter ID and value type (which contains the parameter value). All RAN parameters relevant for Semi-Persistent Scheduling are shown in Appendix table 9.11.

Chapter 8

Conclusion

The future mobile networks aim to satisfy needs of various novel services. One of these services is the Tactile Internet with strict communication requirements. To satisfy the needs of such service, mobile network needs to provide a communication "tailored" to the given service. The mobile networks have introduced concept of network slicing. However, the network slicing over two geographically separated networks has not been realized. Therefore, in this thesis we design a solution for a case of Tactile Internet, represented by remote robot control over two independent mobile networks. The Tactile Internet falls under URLLC service, which works for a single mobile network. In the existing works it has been shown that remote robot control is feasible with current 5G technology, which is a motivation to extend the work towards a more challenging case of two separate networks.

In the thesis we defined the problem of E2E remote control where both Controller and Robot are connected using mobile network and are separated by an internet connection. The impact of communication delay is briefly analysed to determine which parts need to be optimized. From the analysis we have determined that the most critical are delays caused by waiting for access to the channel and transmission time. Therefore, the rest of the thesis aim was to minimize these delays in both UL and DL while minimizing jitter and adhering to transmission error rate.

The proposed solution leverages O-RAN xApps which rely on RIC to access RAN control function and parameters. To jointly optimize both mobile networks (gNBs), we propose to use two xApps, one at each gNB. To reach E2E URLLC connection requirements, a prediction is utilized. An existing prediction is utilized, as the focus of the thesis is on the delay optimization, not on the prediction. To jointly optimize the connection, UL allocation information is shared to the second gNB for DL allocation. The overall system and its behaviour is presented, this includes states before E2E transmission, during the transmission and after the transmission.

Implementation of the proposed solution using currently specified E2SMs was described. The implementation is based on OpenAirInterface 5G network implementation for testing of the fundamental design concept. The solution is based on xApps, which are being introduced in the mobile networks based on O-RAN. Therefore, the proposed solution and its implementation is based on the standard E2SM RAN Control which provided just enough options to realize conceptual testing of the design. The proposed solution can be implemented and deployed in commercial mobile networks. However, as of writing of this thesis neither OpenAirInterface nor SRS-RAN have implemented the standard features needed for implementation. Therefore, a validation step of the proposed solution is still necessary before deployment. Nevertheless, the provided description of the proposed solution should suffice to validate it.

The future work of the thesis would be realization of the implementation, testing and analysis of the proposed solution performance. Moreover, several improvements, including enhancing CQI prediction considering both UL and DL, choosing of the best resources for the transmission, internet connection optimization, RAN and Core setting optimization, intelligent control loops that interact with the predictors, frequency hopping usage for narrow-band interference mitigation could be investigated. However, the most beneficial improvement would be BSR revision and implementation of enhanced BSR according to [58]. /acBSR in its current implementation has several drawbacks that could jeopardize effective resource allocation because our proposed solution depends on accurate BSR values to predict future traffic accurately. The main problem for our use-case is inaccurate BSR estimation which stems from length of convergence of the standard BSR estimation to real value and its association with logical channel id instead of specific UE [58].

Chapter 9

Appendix

The Appendix contains supplementary information from standards that define RAN parameters of interest. It should provide details that are necessary to gain better understanding of the E2SM data structures and RAN Control E2SM.

9.1 E2SM RAN Control Enveloping Structures

When sending or receiving any kind of information to or from RIC the information is sent using a defined structure of Header and Message. Header and Message both have several types of formats which are applicable to specific scenarios. In the implementation we use RAN Control E2SM Header and Message Format 1 which are used for Control Service. Both of the formats are defined below in table 9.1 and table 9.2. Different formats are associated with different RIC Services. Information about which Header or Message format to use with a given RIC Service can be found in [9].

9.1.1 Information Structure definitions

E2SM-RC Control Header Format 1

IE/Group Name	Presence	IE type and reference	Semantics description
UE ID	M	chapter 9.3.10 in [9]	
RIC Style Type	M	chapter 9.3.3 in [9]	
Control Action ID	M	chapter 9.3.6 in [9]	Refer to Section 7.6 in O-RAN standard or table 9.4
RIC Control decision	O	ENUMERATED (accept, reject)	Used only when a Control action is sent as a response to an Insert Indication

Table 9.1: Table adapted from O-RAN E2SM RAN Control standard (chapter 9.2.1.6.1) [9].

E2SM-RC Control Message Format 1

IE/Group Name	Presence	IE type and reference	Semantics description
List of RAN parameters			
-RAN parameter ID	M	9.3.8	Refer to table in Section 8.4
-RAN Parameter Value Type	M	9.3.11	Refer to table in Section 8.4

Table 9.2: Table adapted from O-RAN E2SM RAN Control standard (chapter 9.2.1.7.1) [9].

9.2 E2SM RAN Control Style Types

Each RIC Service in each of defined Service Models (E2SMs) has its own Style Types. Style Type in this instance refers to a set of sub-services available within a given Service. An example for our case is the table below. It defines Style Types available for Control Service in E2SM RAN Control:

Style Type	Style Name	Style Description
1	Radio Bearer control	Used to modify the configuration the Radio Bearer Control (RBC) related parameters and/or behaviours at the E2 Node for a specific UE or a UE group. Belongs to Fundamental level CONTROL Services.
2	Radio resource allocation	Used to modify the configuration the Radio Resource Allocation control related parameters and/or behaviours at the E2 Node for a specific E2 Node, cell, slice, UE and/or QoS Belongs to Fundamental level CONTROL Services.
3	Connected mode mobility control	Used to initiate a connected mode mobility procedure (Handover or Conditional Handover), optionally with Dual Active Protocol Stack (DAPS), for a specific UE towards either a target cell (for HO) or a list of candidate cells (for CHO) Belongs to Fundamental level CONTROL Services.
4	Radio access control	Used to modify Radio access related functions used to control UE access to cells Belongs to Fundamental level CONTROL Services.
5	Dual connectivity (DC) control	Used to initiate Dual connectivity (DC) mechanisms Belongs to Fundamental level CONTROL Services.
6	Carrier Aggregation (CA) control	Used to initiate Carrier Aggregation (CA) mechanisms Belongs to Fundamental level CONTROL Services.
7	Idle mode mobility control	Used to modify Idle mode mobility related functions used to control UE reselection of cells Belongs to Fundamental level CONTROL Services.
8	UE information and assignment	Used for Explicit UE list assignment, UE information report generation and to complete UE identification. These services are used to support other RIC services. Belongs to Fundamental level CONTROL Services.
9	Measurement Reporting Configuration control	Used to control the measurement report configuration
10	Beamforming Configuration control	Used to control beamforming configuration for a specific UE .
255	Multiple Actions Control	Used for multiple actions of the selected fundamental level CONTROL Service style(s). Belongs to Integrated level CONTROL Services.

Table 9.3: Table reproduced from the O-RAN E2SM Control standard (chapter 7.6.1) [9].

9.2.1 Radio Resource Allocation Style Type Control Actions

To access a specific RAN parameter within any Style Type we first need to select a group of parameters that it (the RAN parameter) belongs to. The groups of parameters are called Actions. In the case of Control Service the parameter groups are called Control Action IDs. In chapter 7 we specified a solution using Radio Resource Allocation Style Type. Within this Style Type these parameter groups (Control Action IDs) are available:

ID	Control Action Name	Control Action description	Associated RAN Parameters
1	DRX parameter configuration	To control the configuration of DRX parameters	O-RAN standard: 8.4.3.1
2	SR periodicity configuration	To control the configuration of SR periodicity parameters	O-RAN standard: 8.4.3.2
3	SPS parameters configuration	To control the configuration of SPS parameters	table 9.11 from O-RAN standard: 8.4.3.3
4	Configured grant control	To control the configuration of uplink grants to the UE	table 9.5 from O-RAN standard: 8.4.3.4
5	CQI table configuration	To control the configuration of CQI table.	O-RAN standard: 8.4.3.5
6	Slice-level PRB quota	To control the radio resource management policy for slice-specific PRB	O-RAN standard: 8.4.3.6

Table 9.4: Table reproduced from the O-RAN E2SM Control standard (chapter 7.6.3.1) [9].

A list of the RAN parameters for each of the Control Action IDs can be found in O-RAN E2SM RAN Control specification [9]. In the following sections we focus on parameters for Control Action IDs number 3 and 4 named SPS parameters configuration and Configured grant control respectively.

9.3 Configured Grant Parameters

This section provides additional information necessary to choose correct parameter values when configuring Configured Uplink Grant. Table 9.5 contains all the parameters that can be set when configuring Configured Uplink Grant. Mandatory parameters are highlighted with using **bold** format. We can see that the RAN parameter list contains two structures: main structure "Grant Configuration" (ID 1) and "RRC Configured Uplink Grant" (ID 11) which is nested in the main structure. Grant Configuration is mandatory as it defines all other parameters but RRC Configured Uplink Grant is not. Based on the presence of RRC Configured Uplink Grant two Configured Grant types are differentiated. Configured Grant type 2 does not allow for precise allocation control and thus does not necessitate presence of the RRC Configured Uplink Grant parameter structure. However, in chapter 7 we used Configured Grant type 1 which must have the RRC Configured Uplink Grant parameter structure defined and filled with values.

ID	RAN Parameter	RAN Parameter Value Type	Key Flag	RAN Parameter Values
1	**Grant Configuration**	STRUCTURE		
2	>MCS Table	ELEMENT	FALSE	ENUM {qam256, qam64LowSE}
3	>MCS Table Without Transform Precoder	ELEMENT	FALSE	ENUM {qam256, qam64LowSE}
4	>**Resource Allocation**	ELEMENT	FALSE	ENUM {resourceAllocationType0, resourceAllocationType1, dynamicSwitch}
5	>**Number of HARQ processes**	ELEMENT	FALSE	INTEGER(1..16)
6	>HARQ retransmissions	ELEMENT	FALSE	(Seems like a mistake in the O-RAN standard, element not present in TS 38.331)
7	>**Number of repetitions of HARQ PDU (repK)**	ELEMENT	FALSE	ENUM {n1, n2, n4, n8}
8	>Redundancy Version Format (repK-RV)	ELEMENT	FALSE	ENUM {s1-0231, s2-0303, s3-0000}
9	>**UL Transmission periodicity**	ELEMENT	FALSE	ENUM {period in symbols}
10	>Configured grant timer	ELEMENT	FALSE	INTEGER (1..64)
11	>RRC Configured Uplink Grant	STRUCTURE		(This structure is not MANDATORY see [ref to desc.])
12	->**Time Domain Offset**	ELEMENT	FALSE	INTEGER (0..5119) [slots from SFN = 0]
13	->**Time Domain Allocation**	ELEMENT	FALSE	INTEGER (0..15)
14	->**Frequency Domain Allocation**	ELEMENT	FALSE	BIT STRING (SIZE(18))
15	->**Antenna Port**	ELEMENT	FALSE	INTEGER (0..31)
16	->**Precoding and number of layers**	ELEMENT	FALSE	INTEGER (0..63)
17	->**MCS and TBS**	ELEMENT	FALSE	INTEGER (0..31)
18	->**Path Loss Reference Index**	ELEMENT	FALSE	INTEGER (0..maxNrofPUSCH-PathlossReferenceRSs-1)

Table 9.5: Table adapted from the O-RAN E2SM RAN Control standard (chapter 8.4.3.4) [9]. More details about each of the parameters can be found in TS 38.331 chapter 6.3.2 in the table: "ConfiguredGrantConfig Information Element" [10]. Parameter values were added from the "ConfiguredGrantConfig Information Element" table for reader's convenience. Mandatory parameters are emphasized with **bold** format.

9.3.1 Parameter: MCS Table

Parameters number two and three define theMCS Table. If parameterMCS Table is defined transform precoding is used. When the parameter is not defines lowSE QAM64 is used.

9.3.2 Parameter: Resource Allocation

This is a mandatory parameter. There are three uplink (frequency) resource allocation scheme types defined in [11]. For details refer to standard TS 38.214 chapter 6.1.2 [11]. A brief description of the three types is here:

1. Type 0 - define frequency allocation using Resource Block Group (RBG) bitmap (only available for disabled transform precoding)
2. Type 1 - define frequency allocation by starting RB and the allocation length
3. Dynamic Switch - the allocation type can changed dynamically for each transmission

9.3.3 Parameter: Number of HARQ processes

This parameter is mandatory. Specifies number of HARQ processes used for Configured Grant re transmissions.

9.3.4 Parameter: Number of repetitions of HARQ PDU

This parameter is mandatory. Defines how many times HARQ PDU is repeated. When set to n1, no HARQ repetitions are configured.

9.3.5 Parameter: Redundancy version format

Defines Redundancy Version sequence used for re-transmission. If parameter: Number of repetitions of HARQ PDU section 9.3.4 is set to n1 this parameter has no use, because repetitions are not configured.

9.3.6 Parameter: UL Transmission periodicity

This parameter is mandatory. In table 9.5 this parameter values are not explicitly defined, because of space constraints. Enumerated list of values:

sym2, sym7, sym1x14, sym2x14, sym4x14, sym5x14, sym8x14, sym10x14, sym16x14, sym20x14, sym32x14, sym40x14, sym64x14, sym80x14, sym128x14, sym160x14, sym256x14, sym320x14, sym512x14, sym640x14, sym1024x14, sym1280x14, sym2560x14, sym5120x14, sym6, sym1x12, sym2x12, sym4x12, sym5x12, sym8x12, sym10x12, sym16x12, sym20x12, sym32x12, sym40x12, sym64x12, sym80x12, sym128x12, sym160x12, sym256x12, sym320x12, sym512x12, sym640x12, sym1280x12, sym2560x12

Not all values can be chosen depending on selected Sub-Carrier Spacing (SCS). The following table defines all possible values for SCS choice:

SCS	possible periodicity values in symbols	
15 kHz	2, 7, n $\star$ 14	where n= {1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 128, 160, 320, 640}
30 kHz	2, 7, n $\star$ 14	where n = {1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 128, 160, 256, 320, 640, 1280}
60 kHz with normal CP	2, 7, n $\star$ 14	where n = {1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 128, 160, 256, 320, 512, 640, 1280, 2560}
60 kHz with ECP:	2, 6, n $\star$ 12	where n = {1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 128, 160, 256, 320, 512, 640, 1280, 2560}
120 kHz:	2, 7, n $\star$ 14	where n = {1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 128, 160, 256, 320, 512, 640, 1024, 1280, 2560, 5120}
480 and 960 kHz:	n $\star$ 14	where n = {1, 2, 4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 128, 160, 256, 320, 512, 640, 1024, 1280, 2560, 5120}

Table 9.6: Table adapted from clause: "ConfiguredGrantConfig" in TS 38.331 [10].

This element defines periodicity of transmission in symbols ranging from transmission burst to long intervals between transmissions. More information in clause 5.8.2 in TS 38.321 [59].

9.3.7 Parameter: Configured Grant Timer

This parameter works in conjunction with the previous one to define a periodically repeating transmission. Parameter UL Transmission periodicity defines the interval and Configured Grant Timer defines how many times is the transmission repeated.

9.3.8 Parameter: RRC Configured Uplink Grant

This parameter is optional, however if it is defined parameters 12 through 18 are mandatory. This parameter is in fact a structure which contains all the necessary RRC parameters for Type 1 Configured Grant. Type 1 Configured Grant uses set parameters for the UL transmission whereas in Type 2 the gNB configures the RRC parameters by itself. For tighter control Configured Grant Type 1 is utilized. If this parameter is defined Configured Grant type 1 is used if not the gNB uses Configured Grant type 2 [10].

9.3.9 Parameter: Time Domain Offset

This parameter is mandatory (if section 9.3.8 is defined). Specifies the start of UL transmission and in combination with parameter: UL transmission periodicity consequently sets time of the subsequent transmissions. It is defined as a slot number offset from the SFN = 0 [59, 10]. The exact slot number of N^{th} transmission can be calculated in the following way:

N^{th} transmission slot number =
(timeReferenceSFN × numberOfSlotsPerFrame × numberOfSymbolsPerSlot
+ timeDomainOffset × numberOfSymbolsPerSlot + S + N × periodicity)
modulo (1024 × numberOfSlotsPerFrame × numberOfSymbolsPerSlot),

where SFN is the system frame number, which is a frame counter with range 1-1023.

9.3.10 Parameter: Time Domain Allocation

This parameter is mandatory (if section 9.3.8 is defined). It defines allocation of symbols within a slot. The parameter value ranges from 0 to 15, which corresponds to rows in the following table:

TD Alloc. Value	PUSCH mapping type	K2	S	L
0	Type A	j	0	14
1	Type A	j	0	12
2	Type A	j	0	10
3	Type B	j	2	10
4	Type B	j	4	10
5	Type B	j	4	8
6	Type B	j	4	6
7	Type A	j+1	0	14
8	Type A	j+1	0	12
9	Type A	j+1	0	10
10	Type A	j+2	0	14
11	Type A	j+2	0	12
12	Type A	j+2	0	10
13	Type B	j	8	6
14	Type A	j+3	0	14
15	Type A	j+3	0	10

Table 9.7: Table reproduced from TS 38.214: "Table 6.1.2.1.1-2: Default PUSCH time domain resource allocation A for normal CP" [11].

Supplementary table that explicitly defines K2 values that depend on the selected PUSCH SCS:

PUSCH SCS	j
0	1
1	1
2	2
3	3
5	11
6	21

Table 9.8: Table reproduced from TS 38.214: "Table 6.1.2.1.1-4: Definition of value j" [11].

Table 9.7 has 5 columns each belonging to a different Time Domain Allocation parameter. The first column: "TD Alloc. Value" is the value of

parameter Time Domain Allocation. It serves as a reference to a row which contains the setting for the remaining parameters.
The second column: "PUSCH mapping type" provides only two options: Type A and Type B. PUSCH mapping types define whether to use De-Modulation Reference Signal (DMRS) type A or Type B respectively. DMRS is used to decode PDSCH transmissions. DMRS Type A schedules the reference signal either in the third or fourth symbol. DMRS Type B has the reference signal fixed at the first symbol of the PUSCH transmission [60]. Setting of DMRS Type affects the possible values in the remaining 3 columns: "K2", "S" and "L". These 3 values combined define a value called Start and Length Indicator Value (SLIV). SLIV defines both the length and start of PUSCH allocation as illustrated in the picture below:

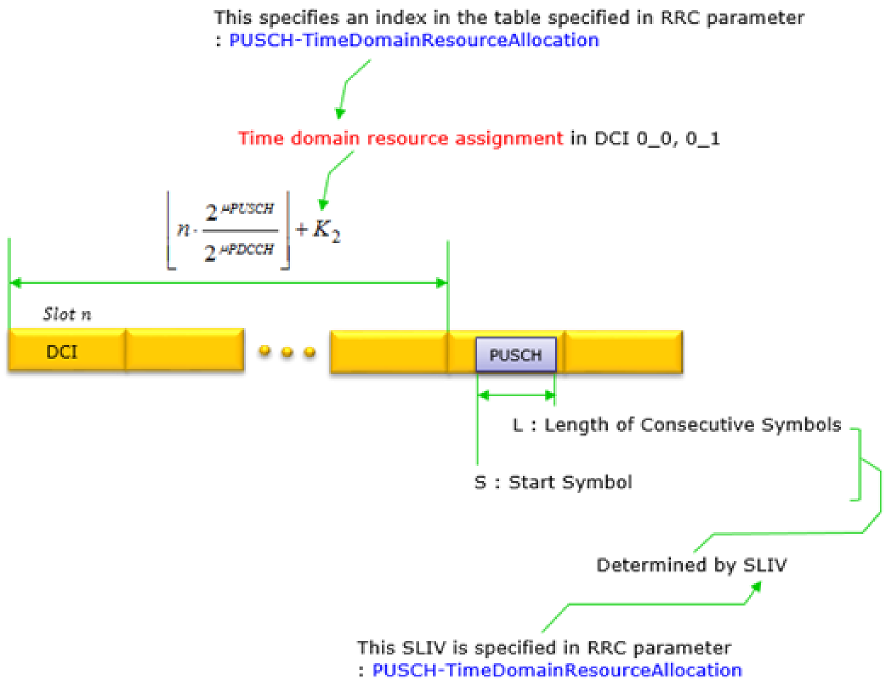

Figure 9.1: Illustration of SLIV reproduced from [8].

Parameter K_2 defines number of slots between scheduled DCI associated with the PUSCH allocation. Parameter S defines the first symbol of the PUSCH allocation. Parameter L defines the length of time domain allocation in symbols. More details can be found in clause 6.1.2 in TS 38.214 [11] and clause 7.3.1 in TS 38.212 [61].

9.3.11 Parameter: Frequency domain allocation

This parameter is mandatory (if section 9.3.8 is defined). Configured Uplink Grant parameter Frequency Domain Allocation specifies allocation in frequency domain. It is defined as 18 bit string each bit is associated with a Resource Block Group (RBG). If a bit is set to 1, then Resource Block

Group (RBG) associated with that bit is allocated. Size of RBGs associated with each bit in the 18 bit string depends on several parameters: Bandwidth Part (BWP) size, and parameter rbg-size. Table 9.9 defines RBG size for all combinations of these parameters. BWP size is a RAN parameter that tells us how big the Bandwidth Part (BWP) for a given UE is. Parameter rbg-size defines how many RBs are in RBG, it has three possible values: configuration 1, configuration 2 and configuration 3 ordered by increasing size. More details can be found in clause 6.1.2 in TS 38.214 [11], and in clause 7.3.1 in TS 38.212 [61].

Bandwidth Part Size	Configuration 1	Configuration 2	Configuration 3
1 – 36	2	4	8
37 – 72	4	8	16
73 – 144	8	16	32
145 – 275	16	16	32

Table 9.9: Table "Nominal RBG size" reproduced from TS 38.214 [11].

Parameter Frequency domain allocation is a 18 bit string which references RBG that are to be allocated for the UE . For illustration of how the selection of RBGs works see table available For a better illustration of the concept see [62]. It is important to note that parameter: Resource Allocation Type described in section 9.3.2 selects the Resource Allocation Type which defines the way frequency allocation is chosen. Resource allocation type 1 allows only continuous RBG allocation, whereas type 0 allocation can be discontinuous.

9.3.12 Parameter: Antenna Port

This parameter is mandatory (if section 9.3.8 is defined). Chooses Antenna Port which is to be used for transmission. For more information about the Antenna Port Concept see ShareTechnote page [63], clause 6.1.2 in TS 38.214 [11] and clause 7.3.1 in Ts 38.212 [61]

9.3.13 Parameter: Precoding and number of layers

This parameter is mandatory (if section 9.3.8 is defined). Parameter is used to choose the configuration of precoding and number of layers. For more information see clause 7.3.1.1.2 in TS 38.212 [61] and clause 6.1.2.3 TS 38.214 [11].

9.3.14 Parameter: MCS and TBS

This parameter is mandatory (if section 9.3.8 is defined). Specifies theMCS index in usedMCS table. Based on description in clause 6.1.4.1 in TS 38.214 [11] we constructed table 9.10 to help determine the table number that is used for given set of parameters.

Transform Precoding	mcs-Table	RNTI
Disabled	256QAM	CS-RNTI
Disabled	low-SE 64QAM	CS-RNTI
enabled	256QAM	CS-RNTI
enabled	low-SE 64QAM	CS-RNTI

Table 9.10: Table adapted from [12] and updated to adhere to [11].

MCS tables are defined in the following table numbers in TS 38.214 [11]:

- low-SE 64QAM in Table 5.1.3.1-3
- 256QAM in Table 5.1.3.1-2

9.3.15 Parameter: Path Loss Reference Index

This parameter is mandatory (if section 9.3.8 is defined). The value of this parameter is used to select a PUSCH pathloss reference signal. More information here clause 7.1.1 in TS 38.213 [64].

9.4 Semi-Persistent Scheduling Parameters

This section provides additional information necessary to choose correct parameter values when configuring Semi-Persistent Scheduling. Table 9.11 contains all the parameters that can be set when configuring Semi-Persistent Scheduling. Mandatory parameters are highlighted with using **bold** format. The gNB scheduler allocates RBs in both time and frequency domains. However, it is evident from table 9.11 the E2SM RC defines only 3 parameters that are available for writing and none of them affects the size of either frequency or time allocation. Only periodicity is available which does not influence the size of the periodic allocation size. Based on description in [57] RAN resources allocated in the first transmission are repeated with periodicity defined by parameter SPS Periodicity. The allocation of the first transmission is allocated automatically by network.

ID	RAN Parameter Name	RAN Parameter Value Type	Key Flag	RAN Parameter Values
1	**SPS-Config**	STRUCTURE		
2	>**SPS Periodicity**	ELEMENT	FALSE	ENUM {ms10, ms20, ms32, ms40, ms64, ms80, ms128, ms160, ms320, ms640, spare6, spare5, spare4, spare3, spare2, spare1}
3	>**Number of HARQ Processes**	ELEMENT	FALSE	INTEGER (1..8)
4	>MCS Table	ELEMENT	FALSE	ENUM qam64LowSE

Table 9.11: Table adapted from the O-RAN E2SM Control standard (chapter 8.4.3.3) [9]. Mandatory parameters are shown in **bold**.

Following sections provides all the additional information needed to choose correct parameter values when configuring Semi-Persistent Scheduling.

9.4.1 Parameter: SPS Periodicity

This is a mandatory parameter. Specifies the scheduling interval (periodicity). It defines several period values in ms. We can only choose one of them not precisely define our own values. TS 38.331 V17.6.0 standard defines new, more flexible periodicity setting: periodicityExt IE [10].

9.4.2 Parameter: Number of HARQ processes

This is a mandatory parameter. Analogous parameter to Configured Up-link Grant parameter with the same name described here section 9.3.3.

9.4.3 Parameter: MCS Table

Optional parameter. Not defining this parameter chooses a value. Value choice is described in TS 38.331 in the SPS-Config IE description [10]. We summarize the conditions for each choice in table below:

Parameter MCS table	PDSCH config parameter condition	DCI Format condition	Chosen MCS table
0	inconsequential		low-SE 64QAM
Not Defined	mcs-table = QAM256	1_1	256QAM
Not Defined	mcs-table-r17 = QAM1024	1_1	1024QAM
Not Defined	none of the above are satisfied		non-low-SE 64QAM

Table 9.12: MCS table choice conditions based on description in [10].

MCS table are defined in the following table numbers in TS 38.214 [11]:

- low-SE 64QAM in Table 5.1.3.1-3
- 256QAM in Table 5.1.3.1-2
- 1024QAM in Table 5.1.3.1-4
- non-low-SE 64QAM in Table 5.1.3.1-1

Chapter 10

List of Abbreviations

2G	Second Generation	1
3GPP	3rd Generation Partnership Project	1
4G	Fourth Generation	5
5G	Fifth Generation	viii
5G NSA	5G Non-Standalone	16
AMF	Access and Mobility Management Function	4
API	Application Programming Interface	8
AUSF	Authentication Server Function	7
BSR	Buffer Status Report	6
BER	Bit Error Rate	12
BLER	Block Error Rate	25
BW	Bandwidth	5
BWP	Bandwidth Part	60

CDRA	Channel-aware Dynamic Resource Block Allocation	17
CI/CD	Continuous Integration / Continuous Deployment	39
COTS	Commercial Off-The-Shelf	39
CPE	Customer Premise Equipment	13
CQI	Channel Quality Indicator	17
CSI	Channel State Indicator	18
CU/DU	Centralized Unit/Distributed Unit	39
D-RBs	Dynamic Resource Blocks	18
DL	Down-link	6
DMRS	De-Modulation Reference Signal	59
DNN	Deep Neural Network	18
DPS	Dynamic-Point Selection	17
DRB	Data Radio Bearer	35
E2AP	E2 Application Protocol	8
E2E	End to End	1
E2SM	E2 Service Model	8
eMBB	enhanced Mobile Broadband	12
FDD	Frequency Division Duplex	12

FDMA	Frequency Division Multiple Access	5
FIFO	First In First Out	32
GPS	Global Positioning System	16
HARQ	Hybrid Automatic Repeat Request	12
KPM	Key Performance Monitoring	9
LTE	Long Term Evolution	16
LTE-A	LTE Advanced	15
MAC	Medium Access Control	5
MANO	Management and Orchestration	1
MCS	Modulation and Coding Scheme	12
MEC	Multi-access Edge Computing	16
MEP	Multi-access Edge Computing Platforms	40
MNOs	Mobile Network Operators	19
MUST	Massive URLLC Scheduling Technique	17
NaaS	Network as a Service	1
NF	Network Function	7
NFV	Network Function Virtualization	1
NFVIaaS	NFV Infrastructure as a Service	1

NSSF	Network Slice Selection Function	7
NRF	Network Repository Function	7
NR	New Radio	12
OAI	OpenAirInterface	39
OAM	Operations and Maintenance	39
OFDM	Orthogonal Frequency Division Multiplexing	12
OFDMA	Orthogonal Frequency Division Multiple Access	5
PCF	Policy Control Function	7
PDU	Protocol Data Unit	7
PHR	Power Headroom Report	6
PoC	Proof of Concept	15
PDSCH	Physical Down-link Shared Channel	26
PRB	Physical Resource Block	16
PTP	Precision Time Protocol	45
PUCCH	Physical Up-link Control Channel	6
PUSCH	Physical Up-link Shared Channel	6
QoS	Quality of Service	7
RAN	Radio Access Network	1

RB	Resource Block	18
RBG	Resource Block Group	59
RE	Resource Element	5
RIC	RAN Intelligent Controller	2
ROS	Robot Operating System	16
RRC	Radio Resource Control	6
RSTP	Rapid Spanning Tree Protocol	15
RTG	Rubber Tie Gantry	15
RTMP	Real-Time Messaging Protocol	15
RTP	Real-time Transport Protocol	15
RTT	Round Trip Time	11
SaaS	Software as a Service	1
SCS	Sub-Carrier Spacing	12
SDK	Software Development Kit	40
SLIV	Start and Length Indicator Value	59
SINR	Signal-to-Interference-plus-Noise Ratio	25
SMF	Session Management Function	7
SMO	Service Management and Orchestration	8

SPS	Semi-Persistent Scheduling	47
TCP	Transmission Control Protocol	31
TDD	Time Division Duplex	12
TDMA	Time Division Multiple Access	5
TTI	Transmission Time Interval	12
UDP	User Datagram Protocol	15
UDM	Unified Data Manager	7
UDRA	Urgency-aware Dynamic Resource Block Allocation	17
UE	User Equipment	3
UL	Up-link	5
UPF	User Plane Function	3
URLLC	Ultra Reliable Low Latency Communication	12
USB	Universal Serial Bus	15
VNFaaS	Virtual Network Function as a Service	1
VPN	Virtual Private Network	13
VUE	Vehicle User Equipment	18

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