Routing and Packet Scheduling in LoRaWANs-EPC Integration Network and in O-RAN

by

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Routage et ordonnancement de paquets dans les réseaux d'intégration LoRaWANs-EPC et d'O-RAN

Chengcheng ZHANG

RÉSUMÉ

Le routage et l'ordonnancement de paquets sont essentiels dans le réseau mobiles, afin de fournir une qualité de service (QdS) pour une multitude d'applications telles que l'Internet des objets de faible puissance, les services cellulaires à haut débit, et les services ultra-fiables et faible latence. Dans ce mémoire, nous étudions les problèmes de routage et d'ordonnance de paquets dans les réseaux d'intégration LoRaWAN-EPC et dans l'O-RAN.

Récemment, les opérateurs de réseaux mobiles ont envisagé une intégration de LoRaWAN dans leur EPC pour améliorer l'interopérabilité et permettre la co-habitation de plusieurs fournisseurs d'applications. Malheureusement, l'architecture actuelle de 3GPP ne permet pas la coexistence de plusieurs passerelles LoRa dans un réseau d'accès mobile, car aucun mécanisme de routage et d'ordonnancement de paquets n'est défini. Par conséquent, la performance du réseau d'intégration est limitée. Dans ce mémoire, nous proposons une solution, permettant à plusieurs passerelles et capteurs de LoRa dans différentes zones d'accéder simultanément aux serveurs d'applications. Nous proposons une méthode pour sélectionner des routes optimales à travers l'EPC, et formulons le problème du routage et d'ordonnancement optimal de paquets pour transmettre les paquets LoRa sur ces routes. Les résultats expérimentaux montrent que la solution proposée peut réduire le délai global de 200 ms en moyenne.

En suite, nous étudions l'application de ce problème dans l'architecture O-RAN qui est une architecture RAN innovante conçue pour révolutionner la 5G et au-delà. O-RAN virtualise les fonctions du réseau de fronthaul en O-CU, O-DU et O-RU, qui sont des extensions des CU, DU, RU définies dans 3GPP. Malheureusement, la communication entre ces éléments n'a jamais été normalisée. Les O-DUs ne peuvent pas fonctionner efficacement dans leur ensemble, ce qui limite la performance d'O-RAN. Ce mémoire propose une solution optimisée permettant à plusieurs O-DUs de communiquer d'une manière optimale avec leurs O-RUs. Nous proposons une architecture pour grouper les O-DUs et formulons le problème de sélection des routes optimales et de mapper des paquets UDP en symboles d'OFDM. Les résultats expérimentaux montrent que le temps de réponse est réduit. De plus, nous concevons un algorithme de programmation dynamique pour chercher la solution optimale globalement, et aussi un algorithme glouton pour approximer la solution optimale.

Mots-clés: LoRaWANs, l'integration de 4G/LTE, routage et ordonnancement, O-RAN, 5G

Routing and Packet Scheduling in LoRaWANs-EPC Integration Network and in O-RAN

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ABSTRACT

Routing and packet scheduling are substantial in mobile networks, in order to provide QoS for a variety of applications ranging from low-power IoT to mobile broadband and ultra-reliable low-latency services. In this thesis, we investigate the routing and packet scheduling problems in LoRaWAN-EPC integration network and O-RAN contexts.

Recently, Mobile Network Operators are considering the integration of the LoRaWAN in their EPC to expand their business, and to improve the interoperability and multi-vendor integration in their networks. Unfortunately, the current integration of LoRa and the mobile access according to the 3GPP architectures does not allow the co-existence of multiple LoRa gateways, because the routing and scheduling mechanisms among them are not defined. Therefore, the LoRa gateways cannot operate together, limiting the overall performance of the integration network. In this thesis, we investigate the problem of integrating multiple LoRaWANs into the EPC, which allows several LoRa gateways and sensors in various regions of LoRa signal coverage areas to access multiple network servers and application servers optimally. We propose methods to select dedicated routes in the EPC resource, and formulate the problem of optimal routing and packet scheduling to forward LoRa packets over the routes. The simulation results show our proposed solution can reduce the by an average value of 200ms.

Next, we apply this problem for O-RAN which is an innovative RAN architecture designed to revolutionize 5G and beyond mobile networks. O-RAN virtualized the fronthaul network functions into O-CU, O-DU and O-RU, which are the extension to the CU, DU, RU defined in 3GPP Release 16. Unfortunately, no standard data communication mechanism has been defined for the communication between these elements. Therefore, O-DUs may not work efficiently in the O-DU pool, limiting the RAN performance. This thesis investigates an optimized solution for routing and packet scheduling, allowing multiple O-DU pools to communicate with their O-RUs optimally. We propose an O-DU pool architecture and formulate the problem of optimal routing and packet scheduling to forward OFDM symbols over the optimal routes and map UDP packet sizes to fragment OFDM symbols. Numerical results show the response time reduces. Moreover, we design a dynamic programming algorithm to find out the optimal global solution and a greedy algorithm to approximate the solution.

Keywords: LoRaWANs, integration, 4G/LTE, routing and scheduling, O-RAN, 5G

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LIST OF ALGORITHMS

LIST OF ABBREVIATIONS

ETS	École de Technologie Supérieure
ASC	Agence Spatiale Canadienne
RPS	Routing and Packet Scheduling
O-RAN	Open Radio Access Network
3GPP	3rd Generation Partnership Project
LoRaWAN	Long Range Wide Area Network
EPC	Evolved Packet Core
eNodeB	E-UTRAN Node B
O-CU	Open Centralized Unit
O-RU	Open Radio Unit
O-DU	Open Distributed Unit
CU	Centralized Unit
DU	Distributed Unit
RU	Radio Unit
OFDM	Orthogonal Frequency-Division Multiplexing
DP	Dynamic Programming
IoT	Internet of Things
LPWAN	Low Power Wide Area Network
CSS	Chirp Spread Spectrum

4G/LTE	4th Generation Long Term Evolution
MNO	Mobile Network Operators
O&M	Operation and Maintenance
RAN	Radio Access Network
4G	Fourth Generation
RRU	Remote Radio Unit
BBU	Baseband Unit
VNF	Virtual Network Function
Low PHY	low physical layer
RF	Radio Frequency
RRC	Radio Resource Control
RLC	Radio Link Control
PDCP	Packet Data Convergence Protocol
MAC	Medium Access Layer
eCPRI	enhanced Common Public Radio Interface
NS	Network Server
AS	Application Server
APN	Access Point Name
GTP-U	General Packet Radio Service (GPRS) in Tunneling Protocol for user plane
S-GW	Serving Gateway

PDN-GW	Packet Data Network Gateway
PDN	Packet Data Network
MME	Mobility Management Entity
RAT	Radio Access Technology
5G	Fifth Generation
URLLC	Ultra-Reliable Low Latency Communications
eMBB	enhanced Mobile Broadband
mMTC	massive Machine Type Communication
C-Plane	Control Plane
U-Plane	User Plane
HSS	Home Subscriber Service
EPS	Evolved Packet System
VPN	Virtual Private Network
MAC	Media Access Control
CTI	Cooperative Transport Interface
P2P	Point to Point
E-UTRAN	Evolved-UMTS Terrestrial Radio Access Network
UNI	User Network Interface
NNI	Network Network Interface
PON	Passive Optical Network

L2	Layer 2
LAN	Local Area Network
IIS	Iterated ILP-based Scheduling
ILP	Integer Linear Programming
Doc	Degree of Conflict
DASP	DoC-Aware Stream Partitioning
TT	Time-Triggered
WLAN	Wireless Local Area Networks
AFAPS	Adaptive Flow Assignment and Packet Scheduling
GBRRS	Greedy based round Robin Scheduling
SDN	Software-Defined Networking

LIST OF SYMBOLS AND UNITS OF MEASUREMENTS

Mbps	Mega bit per second
ms	Millisecond
km	Kilometer
U^i	LoRa gateways in the region i
V	APN links associated to PDNs
E	Edges of EPS bearers
$e_{u^i,v}$	An edge of EPS bearer between the u_j^{th} gateway in the i^{th} region and v_k^{th} APN
$C(\cdot)$	Distance cost function for the dedicated edge of EPS bearer
$BW(\cdot)$	Mapping table for the bandwidth of the edger
$\mu(\cdot)$	Service rate function to generate UDP packets
p_l	The 1^{th} packet size
s	Size of UDP packet
h	Size of the GTP-u header
t_l	The instant time slot of 1^{th} time
x_{ij}	denotes the connection between O-DU and VLAN of links
B_j	denotes the total bandwidth of the j O-DU pool
T_j	is the time required to transmit $s_j(\tau)$ OFDM symbols for the j O-DU pool
K_j	is the maximum number of VLANs that j O-DU pool can associate
$B(\cdot)$	denotes the bandwidth assigned to links associated to the j O-DU pool

$F(\cdot)$	is the loading rate from OFDM symbols to UDP packets
$s_j(\tau)$	is the symbol size of the j O-DU pool at slot τ
p_{jk}	is the packet size of k packet generated by the j O-DU pool
G_j^*	is the minimum response time in j O-DU pool
W_j	is a weighting parameter for the j th O-DU pool
α	is a scale parameter for the heuristic function
n	denotes the total number of O-DU pools in the system

INTRODUCTION

Routing and packet scheduling are substantial in mobile networks, in order to provide the quality of service (QoS) for a variety of applications ranging from low-power IoT in smart city fabrics to mobile broadband and ultra-reliable low-latency services in fifth generation (5G) radio access. The thesis covers two separate problems. We investigate a general routing and packet scheduling problem, and then design specific solutions for the long range wide area network and evolved packet core (LoRaWAN-EPC) integration and open radio access network (O-RAN) use-cases.

The main content of this thesis has been presented in two IEEE conference papers. The first paper entitled "Routing and Packet Scheduling in LoRaWANs-EPC Integration Network" was presented by the conference of IEEE GLOBECOM 2020 Symposium SAC IoTSCC7 [Zhang (2020)], in Taiwan. The second paper entitled "Routing and Packet Scheduling For Virtualized Disaggregate Functions in 5G O-RAN Fronthaul" has been submitted for IEEE ICC 2021 which will be held in Montreal, Canada. Globecom and ICC are two flagship conferences of IEEE Communication Society, and are ranked among the top conferences in the field of telecommunication.

Context and motivations

Recently, the Internet of things (IoT) envisions to connect almost everything to the Internet. The acceleration of the deployment drives the telecommunication industry to allow new standards. The low power wide area network (LPWAN) that is a new technology in the lower power and wide area enables the implementation of a large range of IoT applications such as smart city, smart building, agriculture 4.0, etc. LoRaWAN is a prominent long range wide area of LPWAN technology that operates on sub-GHz frequency over the unlicensed band. A LoRa leverages on the chirp spread spectrum modulation technique of the chirp spread spectrum (CSS) which has characteristics of wide range, low bandwidth, and low battery consumption. LoRa gateway relays packets from sensors to the network server in user datagram protocol and Internet Protocol (UDP/IP) without interpretation, while the network server authenticates packets and manages parameters [Watteyne (2017)]. Two main benefits have pushed the motivation for research on the integration of multiple LoRaWANs with the fourth generation and long term evolution network 4G/LTE core. Firstly, Mobile network operators named mobile network operators (MNO) want to play a significant role in the smart city business to consolidate their deployed network infrastructures to extend their market over multi-vendor deployments, and to minimize the investment cost under their the operation and maintenance (O&M) platform [Pouttu (2017)]. Secondly, the next generation radio access network (NGRAN) conducts the concept of multi-vendor integration and interoperability by running on the virtual functions of 4G/LTE on the edge computing resource, for example, LoRa gateway. The adoption of NGRAN compliant in multi-vendor LoRa gateways will enable more scalable, cost-effective, and plug-and-play LoRaWANs to operate in anytime and anywhere. The coexistence of multiple LoRaWANs in a mobile networks will bring clear benefits to both MNO and LoRa content providers. However, a new routing and scheduling mechanism is required to assure QoS and fair resource assignment to the tenants.

In the LoRaWAN-EPC integration, we investigate the problem of enabling multiple LoRa gateways and sensors in distributed geographic regions to access their network servers and application servers. Figure 0.1 illustrates an example presented [Lopez-Soler (2018)] integrating multiple LoRaWANs with the EPC resource, which includes three domains. In a LoRa signal coverage area, all LoRa gateways listen on the same band to receive an identical copy of the LoRa packet from the sensor as presented [Taneja (2016)]. In this example, we need three serving gateways (S-GW) and two packet data network gateways (PDN-GW) to establish GTP-u tunnels. There is a network server (NS) and an application server (AS) in PDN which reside, for instance, in a public cloud on the Internet. To support the coexistence of multiple LoRaWANs, the integration architecture should be redefined to establish dedicated routes for LoRa gateways to access the EPC resource. In the data plane, the LoRa gateway implements the eNodeB data plane protocol stack to access the EPC resources. The uplink interface of the LoRa gateway encapsulates the LoRa packets into the GPRS tunnelling protocol user plane (GTP-u) [Wich (2018)] tunneling packets over the EPC resource from a S-GW to a PDN-GW. GTP-u is a tunneling protocol over UDP/IP, where GTP-u can support one-to-many and many-to-many for the cascading network architecture. PDN-GW terminates GTP-u tunneling and forwards the LoRa packet to its PDN. The downlink interface of the gateway connects to LoRa sensors. The network server is master in a LoRaWAN to control many slaves of sensors and verifies LoRa packet integrity before forwarding it to the application server. In the control plane, the LoRa gateway integrates the eNodeB control plane protocol stack to call the MME that is the brain in the EPC resource to set up GTP-u tunnels. The MME determines the connection over mappings of GTP-u tunnels on S-GWs and PDN-GWs in the EPC resource. In particular, the problems of dynamic establishment of dedicated routes, routing multiple gateways, and scheduling LoRa packets to minimize response time to access the EPC resource have not been addressed so far.

In the same time, a new mobile network architecture has recently emerged. The Option 7 defined [ETSI (2020)] decouples 4G RAN functions to be installed in the radio remote unit (RRU) and the baseband unit (BBU) at fixed locations in Figure 0.2 where units of RRU and BBU defined in 4G specification are the remote radio unit and baseband unit, respectively. Unfortunately, such architecture still lacks the flexibility to adapt to dynamic services. The O-RAN alliance, based on the 3GPP technical specifications of NGRAN, conceives RAN components using the concept of the network functions virtualisation (NFV). In Figure 0.2, the open radio unit (O-RU) holds the radio function (RF) function and Low PHY function, while RRU has the same functions in 4G. Instead of BBU in 4G, 3GPP uses Option 2 [ETSI (2020)] to decouple the radio resource control (RRC), the packet data convergence protocol (PDCP) functions and the radio link control (RLC), the media access control (MAC), High PHY in the open control unit (O-CU) and the open distributed unit (O-DU) of O-RAN. The F1 interface defined in [O-RAN (2020a)] is the

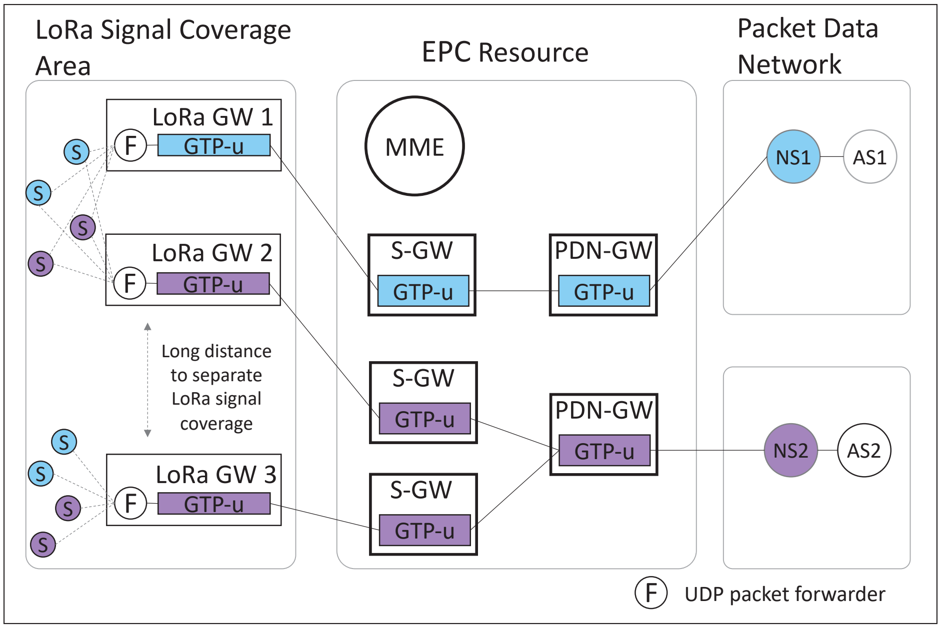

Figure 0.1 Integration of three multiple LoRa gateways with two pairs of the network servers and application servers

interface between O-CU and O-DU in O-RAN. O-DU and O-RU are integrated by Option 7 through a protocol of the enhanced common public radio interface (eCPRI) [O-RAN (2020a)] that is an interface to send control and user data from RRUs to the BBUs.

In O-RAN, 3GPP has defined slicing in the 5G. Three main categories of services in 5G are shown in Figure 0.2. The ultra reliable low latency communications (URLLC) service [ETSI (2019)] requires the O-RAN to minimize the latency and consider the sufficient bandwidth to transfer the ultra-reliable and low-latency traffic . The enhanced mobile broadband (eMBB) service [ETSI (2019)] demands super large evolved mobile bandwidth and excellent quality for the application, e.g. 8K resolution. The massive machine type communications (mMTC) service [ETSI (2019)] relies on the massive connection of machine type communication in the limited resources in the fronthaul network. Each service can be composed of O-RAN virtual elements placed at different locations. The architecture also allows coexistence of multiple vendors as shown in the example in Figure 0.2. In this example, we assume there are two RRUs

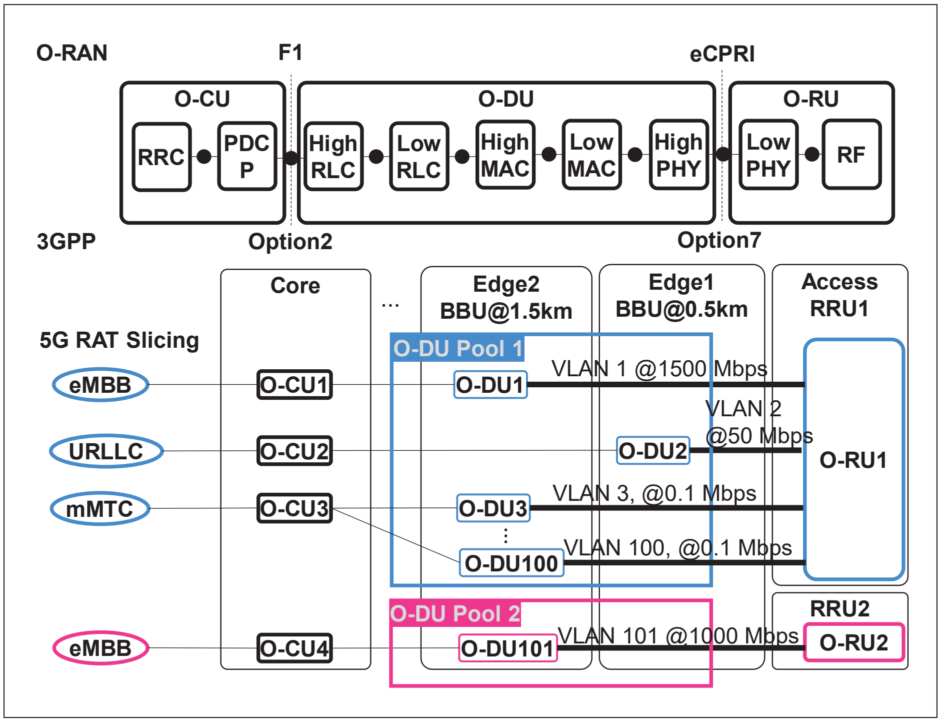

Figure 0.2 O-RAN architecture and an example of O-DU placement for three types of 5G services in the 5G RAT slicing

to support a cell site in each region, and O-CUs, which aggregate and control the resource and the mapping with 5G RAT slicing, are in the fixed location in the core. O-RU1 running on the RRU1 from a vendor in blue color requires O-DU pool 1 created in Edge1 and Edge2 with different distances to maintain three services simultaneously to access 5G RAT slicing. O-RU1 is linked to the edges through VLANs with different bandwidth. The eMBB service which requires a super fast broadband but not extremely low latency, has to place the O-DU1 in Edge 2 at the distance of 1.5 km from O-RU1. The O-DU1 associates VLAN1 with 1500 Mbps high bandwidth. In the Edge 2, the mMTC service requires massive connections from O-DU3 to O-DU100 but low bandwidth of 0.1 Mbps per each to route the traffic from the IoT. On the other hand, the URLLC service requires O-DU2 to be placed on Edge 1 at the distance of 0.5 km to get low latency through VLAN2 with 50 Mbps bandwidth. Another vendor in pink color provides O-RU2 on RRU2 to connect with the O-DU pool 2 to get only the eMBB service

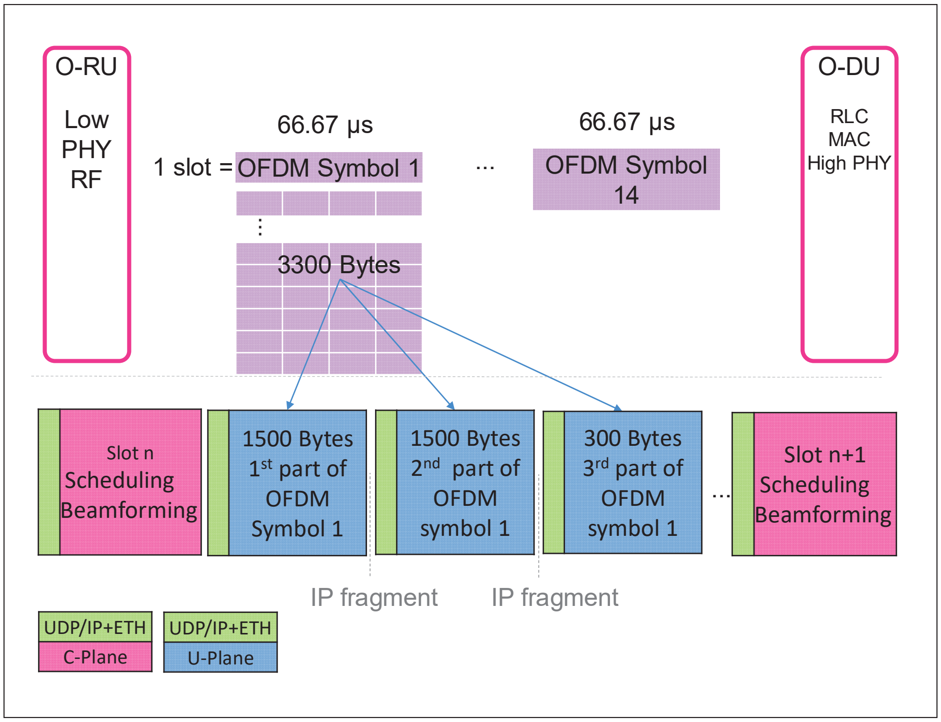

Figure 0.3 An example for an O-DU to fragment the data in an OFDM symbol into 3 UDP packets carried in the capsule of UDP/IP over Ethernet protocol

via O-DU101 through the VLAN101 at 1000 Mbps bandwidth. The aforementioned example suggests a challenging issue of routing and scheduling of an adaptive Ethernet fronthaul for different 5G services in multiple slicing. It is a high-complexity problem because an O-RU may support multiple slices simultaneously to provide different 5G services to subscribers. This requires multiple O-DU pools to be launched at different locations and connected to the O-RU via differentes. In our proposed architecture in the Figure 0.2, we design an O-DU pool, as a group of O-DUs connected to the same O-RU. Each O-DU in the same pool provides different network characteristics based on the service requirement in the RAT slicing. We propose then a solution to route traffic from the O-RU to O-DU at an optimal physical distance and with an optimal bandwidth to meet RAT slicing requirements. Our proposed solution is different from the conventional VLAN that is mainly used to separate traffic in the Ethernet. We combine the routing problem with the packet scheduling problem to provide an integral solution. The scheduling problem determines the optimal packet size and rate on the VLAN to carry 5G the orthogonal frequency-division multiplexing (OFDM) symbols. It is also a challenging problem in O-RAN because 3GPP has defined multiple waveform parameters, which results in various sizes of OFDM symbols according to 5G numerology parameter setup. However, the eCPRI protocol which links O-RU to O-DU is based on UDP protocol with a limited payload size of 1550 Bytes. Therefore, the O-DU must fragment the OFDM symbol into smaller pieces to fit in the UDP payload. Although O-RAN architectures allow the co-existence of multiple O-DU pools and O-RUs, it has not defined any OFDM symbols scheduling mechanism for mixed numerology parameters used on O-DU. Therefore, selecting an optimal UDP loading rate to fragment OFDM symbols to UDP payload is required to enable multiple O-DU pools working efficiently together in an O-DU pool. Figure 0.3 presents an example of this problem. The O-DU sends OFDM symbols to its O-RU over an Ethernet-UDP/IP network. An OFDM symbols in each slot in numerology 0 has $66.76\mu s$ length. After the C-Plane data arrived in the O-RU that schedules to plot the upcoming OFDM data symbol over its array antenna to do beamforming, O-DU starts fragment its OFDM symbol into a dedicated length to fit the UDP payload size in the U-Plane, which will be carried over the encapsulated in IP over the Ethernet network. From our example shown in Figure 0.3, the first OFDM symbol has 3300 bytes of binary data, while each UDP packet has a payload of a maximum of 1550 bytes. If O-DU schedules UDP packet size as 1500 bytes, the third UDP packet takes 300 bytes. It is a bad scheduling, because it wastes the utilization of the bandwidth that causes delay. If O-DU schedules in small packet size, it is also bad scheduling and well explained in Figure 3.5 because of the delay. The problem becomes even more challenging if we inverse the objective function to place O-DUs that are initiated, launched and deleted dynamically. It scales the volume of connections and takes the migration from one location to another depending on the demand of subscribers' behaviors in the network slices.

Objectives of the thesis

The main objective in the thesis is to optimize the routing and scheduling schemes for LoRaWAN-based IoT services and O-RAN. This objective is divided into two sub-objectives (SO), as follows.

SO1, routing and packet scheduling in the LoRaWAN-EPC integration network:

- investigate a practical implementation of integration by taking the advantages of the HSS component that is a database in the EPC. Then, propose a new optimal routing and packet scheduling method to forward data from LoRa gateways.
- propose a model of optimal routing over dedicated routes in the EPC resource.
- propose a packet scheduling model in the LoRa gateway to encapsulate LoRa packets according to the arrival LoRa traffic and the bandwidth of the dedicated route in the EPC resource.
- carry out numerical simulations to evaluate the performance of the integration.

SO2, routing and packet scheduling in the O-RAN:

- propose a new architecture of O-RAN to support 5G services in the 5G slicing.
- propose an optimal routing model and a packet scheduling model to route and encapsulate UDP packets according to the arrival symbol rate on the links between the O-DU pool and O-RUs to meet 5G requirements of minimal costs.
- design an optimization algorithm to solve the joint optimization problem of routing and packet scheduling. In addition, design an approximative algorithm to approximate the optimal results in nearly real-time.

Thesis organization

This thesis includes an introduction, three chapters and a conclusion.

In Introduction, we articulate the context and motivation in order to claim the research problem, objectives in LoRaWAN-EPC integration and O-RAN. and we also define the objectives of this thesis.

In Chapter I, we review the state-of-the-art. On LoRaWAN and EPC integration methods in scenarios regarding the 3GPP user and non-3GPP user, as well as the evolution from RAN to O-RAN and the introduction of multiple 5G RAT.

In Chapter II, we propose our methodology to achieve the objectives. We present our system models and the mathematical formulation of the routing and scheduling problems. We also present our algorithmic solutions to solve the optimization problems.

In Chapter III, we present experimentation that validate our proposed solutions, and then the obtained results.

In Conclusion, we summarize the generalization of routing and packet scheduling problem in the integration of LoRaWAN-EPC and O-RAN, and the future work.

CHAPTER 1

LITERATURE REVIEW

In this chapter, we review the routing and packet scheduling (RPS) mechanism and algorithms that solve start-of-art problems in IoT and 5G network. We also review the current solutions for the integration of LoRaWAN-EPC, and 5G O-RAN. In the Table 1.1, we present a summary of our literature review. It lists current papers studied on routing and scheduling packets in IoT multihop network, software defined networking and heterogeneous wireless networking as well as the integration for the current architecture of LoRaWAN-EPC and the current topology of O-RU and O-DU in O-RAN.

1.1 Routing and packet scheduling

1.1.1 RPS in IoT multihop networking

Many IoT applications (e.g. safety-critical system, and underground mining monitoring system) require communication protocols to support stringent timely delivery guarantees, to reduce the disturbances in real-time multihop network. However, the implementation of such network is very challenging because the system can suffer from a critical fault when a small portion of packets fail to be delivered in time [Deng & Hou (2019)] without having complete information of all future packet arrivals. Prior work [Deng & Hou (2019)] solved the stringent timely delivery problem by proposing a low-complexity algorithm using the primal-dual method to guarantee the timely delivery of most packets in large networks with very high timely delivery requirements. The algorithm leverages an online policy which has several important features to achieve good performance.

Another difficulty in the implementation of such network is to provide QoS in the real time IoT network. An unexpected disturbances may occur with unexpected disturbances in the real time. [Zhang (2019)] solved the unexpected disturbances in real time by proposing an algorithm of fully distributed packet scheduling framework, which can guarantee a fast response to unexpected

Table 1.1
Literature Review

Topic	Feature, Pros and Cons
Routing and packet scheduling [Deng,Han & Hou (2019)] [Zhang,Tianyu (2019)] [Mohamed (2019)] [Sudhakar (2019)] [Chen (2015)]	**Feature** RPS in IoT multihop networking. RPS in software defined networking. RPS in heterogeneous wireless networking. **Pros:** Two ways of traffic partitioning: Graph-Based Stream Partitioning and DoC Aware Stream Partitioning. **Cons:** Not concern the solution to combine routing and packet scheduling.
LoRaWAN-EPC integration [Taneja (2016)] [Lopez-Soler (2018)] [Pouttu (2017)] [ETSI (2018)]	**Feature:** LTE-WLAN aggregation and LTE WLAN radio-level integration with IPsec tunnel and LoRaWAN-EPC Secure Integration Proposal. **Pros:** Use LTE security to integrate LoRaWAN security with two session keys. Use C-Plane and U-Plane of EPC core to initiate a route. **Cons:** Not concern the co-existence of multiple LoRaWANs integration and the PRS problem.
O-RU and O-DU integration in O-RAN [Kumbhani (2020)] [Sudhakar (2020)]	**Feature** 5G multiple slicing with O-RAN and ORAN topology. **Pros:** Shows advantages of aggregation given by 1:1 and 1:n topology of O-RAN. **Cons:** Not concern multi-vendors Not discuss mapping between the 5G slicing services and RPS in O-RAN .

disturbances by the degradation of the performance while meeting the timing and reliability requirements of all critical tasks.

The multihop networking also requires to be aware of time sensitivity in such large scalability. Prior work from [Mohamed (2019)] proposes the mechanism to compute no-wait schedules and multipath routing for the large scale time sensitive network. In the context of the low latency communication over Ethernet architecture, RPS becomes hard problem because of the restrictions, such as queuing delay and packets collisions. To enable the time-aware scheduling, [Mohamed (2019)]introduces three methods. The first method is to achieve high scalability of packet scheduling by fragmenting the set of TT streams into multiple groups. The IIS deals with the incrementally added group of fragmentation to the schedule. The second method of DASP improves the success rate of the IIS proposed in the first method. Finally, DAMR is multipath routing in order to achieve fault tolerance.

The aforementioned problems defined in the IoT network can be solved with a routing model and packet scheduling model. However, no prior work has proposed to combine routing and packet scheduling to provide a joint RPS solution.

1.1.2 RPS in heterogeneous wireless networking

The heterogeneous wireless infrastructures enable subscribers to access the Internet with various cellular networks including 3G GPRS, 4G LTE, WLAN, etc. Current 5G architecture implements a greedy and Round Robin algorithm for packet scheduling. The control of data traffic over the 5G network is a challenging task, because the resource block scheduler in the downlink has to optimize the channel utility to map 5G data traffic onto 5G resources. Prior work [Sudhakar (2019)] defines a framework based on the resource scheduling by GBRRS method, which controls the allocation to schedule data packets on the resource blocks.

The connectivity in the heterogeneous network requires the establishment of multiple paths that enable flow assignment and packet scheduling in limited wireless resources to support high bandwidth and low latency in transmissions. Prior work [Chen (2015)] introduces the AFAPS framework that effectively integrates the flow assignment and packet scheduling. Flow assignment is a filling scheme to maximize flows in the delay constrained traffic over heterogeneous networks. Packet scheduling is an alternative path interleaving scheme to load the packets over various bandwidths of multiple communication paths within the delay constraint.

Flow assignment in routing and packet scheduling is a challenging problems in the heterogeneous network. Separate optimization models can give solutions for each problem. However, no optimal model combining routing and packet scheduling to provide a joint RPS solution has been proposed so far, therefore, prior work often lacks of consistency when considering routing and packet scheduling in parallel manner.

1.2 LoRaWAN-EPC integration

1.2.1 LTE-LPWA integration network

LTE-LPWA integration [Taneja (2016)] is an architecture to integrate LoRa gateways with EPC core network through a LTE eNodeB. Prior to the integration, a LoRa gateway has to implement a 4G/LTE cellular module in the uplink port to transmit LoRa data to eNodeB via E-UTRAN-Uu interface of the radio air. Because of the same band that all LoRa gateways operate on, a signal transmitted from the LoRa sensor may propagate to all LoRa gateways located in the region. The gateway will forward the LoRa frame to eNodeB through the radio air interface. Therefore, there are multiple copies routed in the EPC resource from a signal LoRa sensor. It may cause congestion and leaves a heavy traffic in the limited resource of EPC core. [Taneja (2016)] presents a mechanism to cooperate multiple LoRa gateways by a central controller. Each LoRa gateway can exchange the information to cooperate and update with the central controller to reduce the duplicated copies.

Prior work [Taneja (2016)] is a solution of semi-integration architecture. It does not fully leverage the 4G/LTE resource provided for the integration, therefore, the MNO cannot operate and manage the LoRa gateway through the existing OSS architecture of maintenance and administration. Even though it may reduce the duplicated traffic, it requires to build up a second network to manage the connection of LoRa gateways and the central controller.

In the thesis, we investigate a joint optimization problem of routing and packet scheduling problem.

1.2.2 Single LoRaWAN and EPC integration

Two papers [Lopez-Soler (2018)] and [Pouttu (2017)] introduce the integration architecture of a single LoRaWAN network with EPC network based on the technical specification defined by 3GPP [ETSI (2018)] which is the architecture enhancements for non-3GPP accesses. The LoRa gateway has an eNodeB protocol stack. Therefore, the LoRa gateway plays the role of a LoRa gateway to receive the LoRa signals in the UNI port regarding the relay node in the LoRaWAN, and in the same time, it acts as a eNodeB in the NNI port regarding the access unit in the EPC core network. The U-Plane traffic in the EPC resource is carried over the GTP-U tunnel that is designed based on the UDP packets through S1-u interface to forward the LoRa packet by the encapsulation into the UDP packet. In the C-Plane, MME controls the eNodeB protocol stack in the LoRa gateway to manage the connection of GTP-u tunnels. The duplication problem can be solved by two session keys by the LoRa network server and application server. With the network session key, LoRa network server check the data integrity to reject the data from unregistered sensors. The LoRa application server uses the application session key to hold the confidentiality by the encryption and decryption of the LoRa payload when forwarding in the EPC resource. [Pouttu (2017)] implements the integration of the LoRaWAN through OpenEPC core network.

Prior work [Lopez-Soler (2018)] and [Pouttu (2017)] require both data and control planes to integrate a single LoRa gateway with the EPC resource. The integration of multiple LoRa gateways into EPC is still limited at the architectural level, and the operational complexity is not considered. Unfortunately, a single LoRa gateway cannot afford the requirements of MNOs who want to consolidate their wireless infrastructure to provide LoRaWANs for widely distributed IoT distributions.

In the thesis, we investigate the integration with multiple LoRaWANs with EPC. Furthermore, we apply routing and packet scheduling to the integration of multiple LoRaWAN with EPC.

1.3 O-RU and O-DU integration in O-RAN

1.3.1 5G multiple RAT and Open-RAN

In [Kumbhani (2020)], small cells are deployed alongside homogeneous macro cell networks, which belong to multiple RAT that are the radio access technology in 5G. The 5G technical specification [ETSI (2020)] slices services for multiple 5G RAT to meet these increasing demands of eMBB, URLLC, and mMTC. This slicing requires the separation of multiple functions defined from the single network node to multiple nodes in order to reaction the network characteristics demanded by eMBB, URLLC and mMTC. The RAN aggregation unit routes the traffic from gNB-DUs through Xd interface by the transport protocols of GTP-U, GRE or SDAP. In the paper [Sudhakar (2020)], the authors present the evolution of O-RAN that separates the gNB-DU by two units known as O-RU and O-DU. They also illustrate of the O-RAN topology that the O-DU may connect multiple O-RU with a physical distance.

Prior works [Kumbhani (2020)] and [Sudhakar (2020)] dealing with O-RAN integration are still limited at the architectural level and ignore the operational complexity. In particular, the dynamic establishment of a dedicated link, routing multiple O-DU pools, and scheduling UDP packets to minimize response time from the O-DU pool to O-RUs have not been addressed so far.

In the thesis, we design a new architecture of O-RAN to integrate multiple O-RUs and O-DUs. We investigate the routing and packet scheduling problem in the integration.

CHAPTER 2

METHODOLOGY

In this chapter, we discuss the methodology for routing and packet scheduling problems in both LoRaWAN-EPC integration and O-RAN. The methodology for each problem consists in three parts. Firstly, we present the technical analysis of LoRaWAN-EPC integration and O-RAN. Secondly, we generalize the RPS problems and abstract them into mathematical models. Finally, we proposed algorithms to solve the joint RPS problems.

2.1 LoRaWAN-EPC Integration Network

2.1.1 System Description

Figure 2.1 shows an example of three LoRa gateways accessing the EPC resource to connect to two pairs of NS and AS. This integration inherits the architecture presented in Figure 0.1 except two main differences. Firstly, we partition the entire LoRa coverage area into many regions to roll out multiple LoRa gateways with the minimum overlapping between regions. In the smart city, we assume that there are multiple service providers who intend to deploy their services of IoT applications in any given region. In this assumption, it introduces a problem that different service providers would like to rollout their exclusive LoRaWAN networks under the same region. Because the MNO wants some gateways to be spared gateway in case to replace the broken one without a replacement by an onsite visit, it requires MNO to deploy a larger number of LoRa gateways than the number of service providers. After the installation, the running gateways from different service providers working together may cause the interference. It can be solved by introducing a control of the mechanism. According to LoRaWAN specification, all gateways work the same LoRa bands over all channels [(2017) (Semtech)]. For example, all gateways in Region 1 receive the same copy of the LoRa packet sent from a sensor [Taneja (2016)]. At the LoRaWAN activation stage, a LoRa sensor uses its two fabricated keys to register with a network server, which establishes two sessions to verify the network integrity and

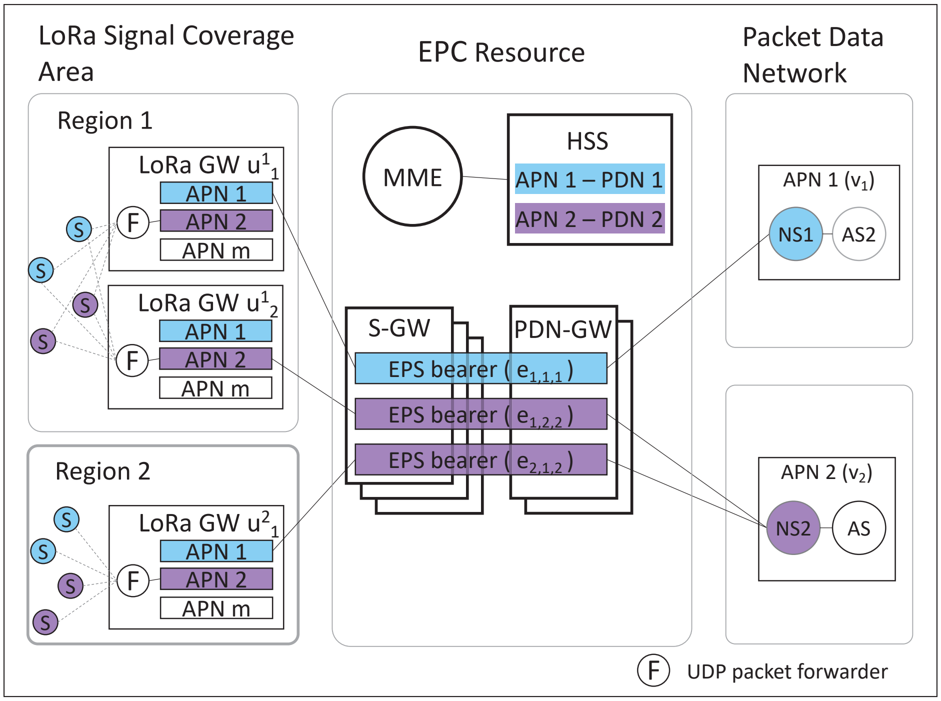

Figure 2.1 Three LoRa gateways calling EPC procedure to establish dedicated routes of EPS bearers to connect with two pairs of network servers and the application servers

confidentiality in a LoRaWAN. The network server filters its appropriate data. For example, the network server in APN 1 in Figure 2.1 will accept only packets sent from LoRa sensors colored in blue, and so does the network server in APN 2. MNO can activate gateways from the spared one connecting to NS and AS, and deactivate running gateway to the spared one. In this case, the system may provide a more flexible routing mechanism to let each LoRaWAN accessing EPC resources with optimal routing based on their cost.

Secondly, our proposed system uses APN to set up dedicated routes of the EPS bearers for LoRa gateways to access the EPC resource tunnels over GTP-u tunnels. The APN represents the VPN to establish GTP-u tunnels to forward packets from a LoRa gateway through an S-GW and a PDN-GW to the corresponding PDN where NS and AS are located [ETSI (2018)]. We store profiles in the HSS, which contains the mapping from the virtual link of APN to its destination PDN. For instance, in Figure 2.1, we call for APN 1 to set up a tunnel to PDN of APN 1. We

Table 2.1 Example of EPS bearer service rate

Type of EPS bearers	UDP generating rate
2Mbps	1 UDP packet per 6ms of unit time
4Mbps	1 UDP packet per 3ms of unit time
6Mbps	1 UDP packet per 2ms of unit time
10Mbps	1 UDP packet per 1ms of unit time

assume each APN has unique information identified in the EPC resource. The EPS bearer is an end-to-end GTP-u tunnel from a LoRa gateway to a PDN-GW. At the attachment procedure, a LoRa gateway sends a request to the MME to apply an EPS bearer to its desired PDN. The MME looks up the HSS database to set up an EPS bearer and provides EPS bearer ID to identify from other bearers. After the establishment of the EPS bearer, the gateway uses the UDP packet forwarder to forward LoRa packets to the corresponding PDN.

We model the LoRa gateways, APNs and EPS bearers by the weighted bipartite graph $G(U^i, V, E)$. Figure 2.1 shows a set of nodes in U^i that are LoRa gateways in the ith region counted from 1 to $\left|U^i\right| \in \mathbb{Z}^+, \forall i \in [1, n]$. A node in the set of V starting from 1 to $|V| \in \mathbb{Z}^+$, represents a PDN network associated with an APN name, which corresponds to a pair of NS and AS. An EPS bearer is denoted as an edge $e_{u^i,v} \in E$ as the ith region, u_j^{th} LoRa gateway, and v_k^{th} APN, where E represents virtual links identified by a unique APN [Hou (2019)].

To enable the integration of multiple LoRa gateways and applications servers through the EPC, two problems have to be addressed, namely the routing problem and the packet scheduling problem. The routing problem is to identify the optimal routes from EPS bearers connected to the gateway, and the LoRa packet scheduling problem is to minimize system response time in the individual gateways. We solved the problems by using the algorithm of Minimum-Weighted Bipartite Matching to find out the optimal routing, and by applying the various EPS bearers to calculate the response time in LoRa gateway in the same time.

2.1.2 LoRa gateway routing model

According to the 3GPP specification [ETSI (2018)], by the configuration of APN information on a LoRa gateway, the gateway may establish plenty of routes identified as EPS bearers in EPC resource to access all NSes in the PDN. Each EPS bearer guarantees the quality of service to specify the bandwidth that is the service rate to allow GTP-u tunnel packets passing through. EPS bearers connecting to LoRa gateways are defined with various constraints. For example, the different LoRa gateways located in the same region cannot connect to the same destination IoT application server. A network server that associates an application server can connect to multiple gateways located in different regions. We formulate our problem as:

$$\exists\, M \subseteq E, \tag{2.1}$$

where it subjects to

$$\forall\ \left(u_1^i, v_1\right), \left(u_2^i, v_2\right) \in M, \tag{2.2}$$

$$u_1^i \neq u_2^i, v_1 \neq v_2. \tag{2.3}$$

In the equation (2.1), we represent routing as a bipartite matching M that listed all the possible edges to denote every EPS bearer that connects one of APN identity in the LoRa gateway to one of the PDN domain. The matching M has to satisfy constraints that are (2.2) and (2.3) that a LoRa gateway can only use one APN identity to connect to the corresponding PDN domain.

Moreover, there are no more than two gateways in the same region that can connect to the same destination for the PDN domain. We can use a simple algorithm of the weighted bipartite graph to iterate all the possible combinations of EPS bearers from the matching function M until we find the optimal cost in minimum distance between LoRa gateway and PDN domain [Hou (2019)].

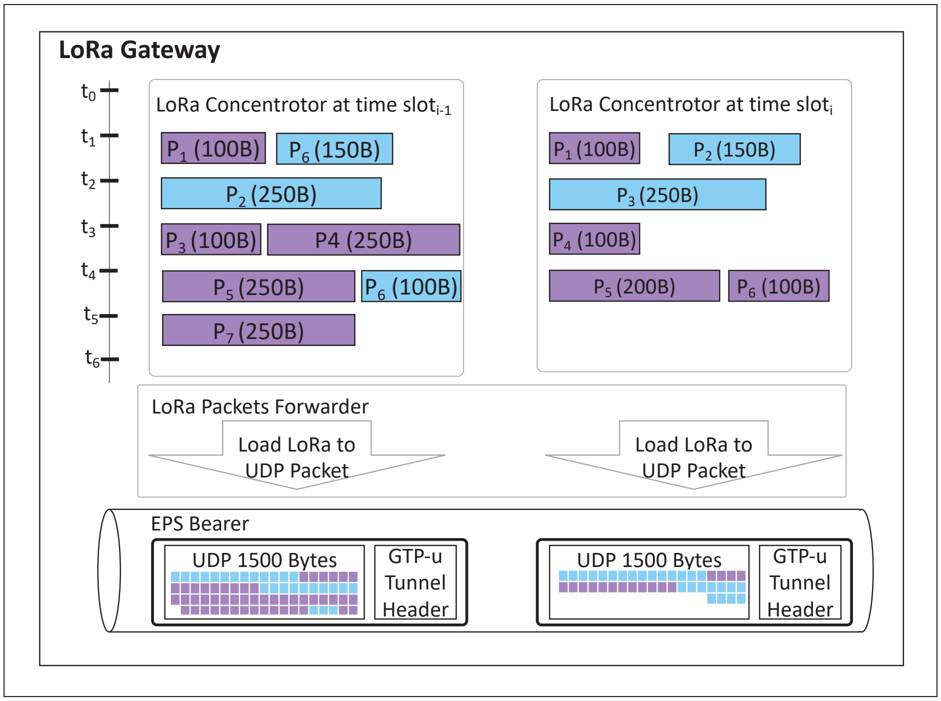

Figure 2.2 The example of a LoRa gateway to schedule two-time slots of LoRa packets over a 2 Mbps bandwidth of a dedicated route of the EPS bearer

2.1.3 LoRa packet scheduling model

Figure 2.2 shows an example in which a LoRa gateway forwards data packets through a 2 Mbps bandwidth of the EPS bearer. Based on Table 2.1, the gateway generates a UDP packet for the GTP-u tunnel for every 6 ms. The value of the time slot is the duration of $t_6 - t_0 = 6$ ms, where t_0 is starting at 0 ms. The LoRa concentrator interprets the LoRa frame in the signal to LoRa packets. In the time $slot_{m-1}$, the LoRa concentrator interpreted seven packets, in which three packets are from APN 1, and four packets are from APN 2. The total packet size of 1450 Bytes is smaller than the fixed UDP packet size. LoRa gateway has a UDP packet forwarder to schedule received LoRa packets into the UDP packets of the GTP-u tunnel. The loading rate defined in [(Semtech)] is depending on the maximum packet size of 250 Bytes, which is 250 Bytes per 1 ms. Therefore, 1450 Bytes of LoRa packets require 5.8 ms so that there is 0.2 ms delayed in response time. In the next time $slot_m$, the LoRa concentrator captured six packets from all sensors. The total LoRa packets have a size of 900 Bytes, less 1500 Bytes of the fixed UDP size. The loading rate is also 250 Bytes per 1 ms. Therefore, it requires 3.6 ms to load 900 Bytes so that there is 2.4 ms delayed in response time in the time of $slot_m$.

The problem here is to determine the bandwidth from optimal routing of the EPS bearer for appropriate scheduling of arrival LoRa packets defined in [Chen (2015)]. We need to identify a policy to combine EPS bearers that follows constraints in the optimal routing in the EPC resource. The policy can be setup regarding the selection of bandwidths. For example, we can either consider the random selection or control the combination of the lowest or highest bandwidth, so that we can evaluate the performance by the delay in the response time.

We formulate a flow of LoRa packets that arrive in a time interval $[t_0, t_L]$. The flow consists of L LoRa packets $p_1, p_2, \cdots, p_L$. The packet p_l in the flow generated by the LoRa RF concentrator at time t_l, where $t_l \in [t_0, t_L]$. And a LoRa packet is denoted as $P = \{(p_l, t_l)\}$, where $t_0 < t_1 < t_2 < \cdots < t_L$. We propose the UDP packet loading rate model, by using L LoRa packets in the flow of LoRa traffic to fill up a UDP packet. We derive the LoRa packet forwarder shown in Figure 2.2 that is the shaper of the loading rate, as:

$$r = \max_{1 \le l \le L} \left\{ \frac{p_l}{t_l - t_{l-1}} \right\}, \tag{2.4}$$

where it reshapes the LoRa packets with the maximum packet size max p_l over unit time $t_l - t_{l-1}$ to fit the maximum size of the UDP packet.

The weight function is defined by the bandwidth between a LoRa gateway and a network server, as:

$$\mu(e_{u^i,v}) = \left\lfloor \frac{s+h}{BW(e_{u^i,v})} \times \frac{1}{1000sec} \right\rfloor, \tag{2.5}$$

where the decision variable $e_{u^i,v}$, an EPS bearer from the u_j gateway in the region i to the PDN v_k. It is an end-to-end GTP-u tunnel through eNodeB, S-GW and PDN-GW. By LoRa specification [Taneja (2016)], the packet size can vary from 11 Bytes to 250 Bytes. All available EPS bearers corresponding to the LoRa gateway are identified by APN names which are defined

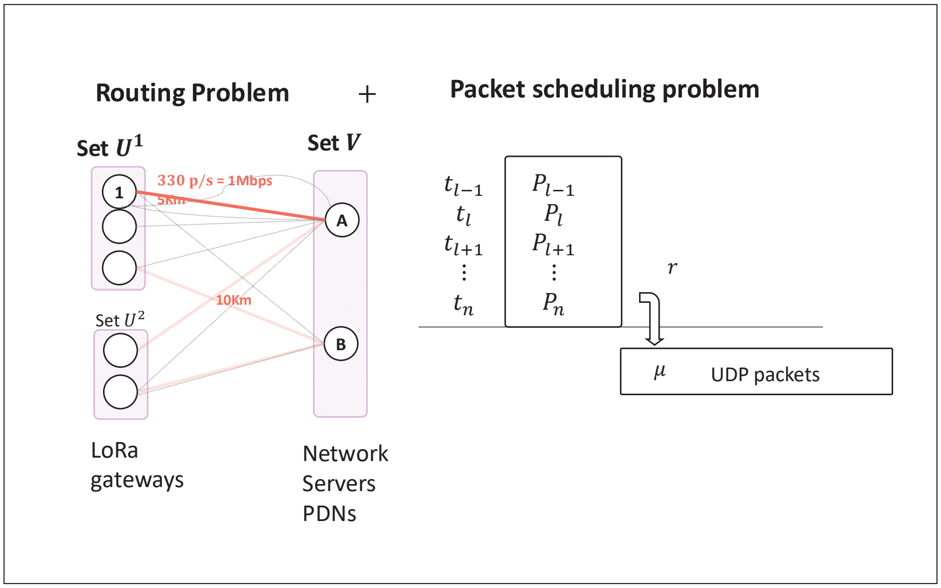

Figure 2.3 Joint RPS model for LoRaWAN-EPC

into four types of bearers, in Table 2.1. We fix the UDP packet size s and header size h to simplify the system complexity. $BW(e_{u^i,v})$ denotes bandwidth which means the rate of UDP packets transmitted in the EPS bearer of $e_{u^i,v}$. The equation 2.5 represents the service rate μ that generates a UDP packet in the periodic duration $(s+h)/BW(e_{u^i,v})$ in ms. Therefore, we use the maximum shaping rate for every UDP packet. In the region, the LoRa gateway has its default bandwidth of the service rate to make the UDP packet. We calculate an example of the service rate based on the given function of bandwidth $BW(\cdot)$ for a specific EPS bearer $e_{u^i,v}$ in Table 2.1.

2.1.4 Optimization model

In our formulation we solved the problem by combining the routing problem of weighted bipartite graph and the scheduling problem to minimize the system response time. The solver is executed at the beginning of the initialization by Mohamed (2019). Once the integrated system runs out the optimal routing and the policy of scheduling, it remains unchanged until the next periodic execution of the solver.

The objective function is to minimize the response time on each LoRa gateway in the system by joint routing and packet scheduling model presented in Figure 2.3, formulated as:

$$\underset{e_{u^i,v}\in M}{\text{Min.}} \sum_i \sum_u \sum_v \frac{1}{\mu(e_{u^i,v})} - \frac{\sum_l p_l}{r}, \tag{2.6}$$

where the weight function of service rate $\mu(\cdot) \in \mathbb{Z}^+$ in (2.6) is to generate UDP packet indicated by the decision variable $e_{u^i,v}$, where $u^i \in U^i$ and $v \in V$. The goal is to determine the optimal routing in the matching M minimizing the system response time.

The objective function of (2.6) subjects to constraints which are formulated as:

$$\sum_l p_l \leq s, \forall l \ni 1 \leq l \leq L, \tag{2.7}$$

$$\sum_v e_{u^i,v} = 1, \quad \forall u^i \in U^i, \tag{2.8}$$

$$\sum_{u^i} e_{u^i,v} = 1, \quad \forall v \in V, \tag{2.9}$$

$$e_{u^i,v} \geq 0, \quad \forall u^i \in U^i, v \in V, \tag{2.10}$$

$$e_{u^i,v} \in \mathbb{Z}^+, \quad \forall u^i \in U^i, v \in V. \tag{2.11}$$

The first constraint (2.7) is assumed from the LoRa concentrator. LoRa network server uses a minimum size of 11 Bytes that can contain a message to control LoRa MAC parameters on LoRa sensors. LoRa sensors can reply to acknowledge or transmit information in the size of the message up to 250 Bytes to IoT application. The variables $e_{u^i,v}$ are restricted to constraints of connection (2.8) (2.9) (2.10) and the constraint (2.11) of integer values.

2.1.5 Algorithmic solution

We apply the algorithm of the minimum weighted bipartite graph [Öncan; İ. K. Altınel (2018)] to solve the bipartite graph of M in the objective function, which identifies EPS bearers named

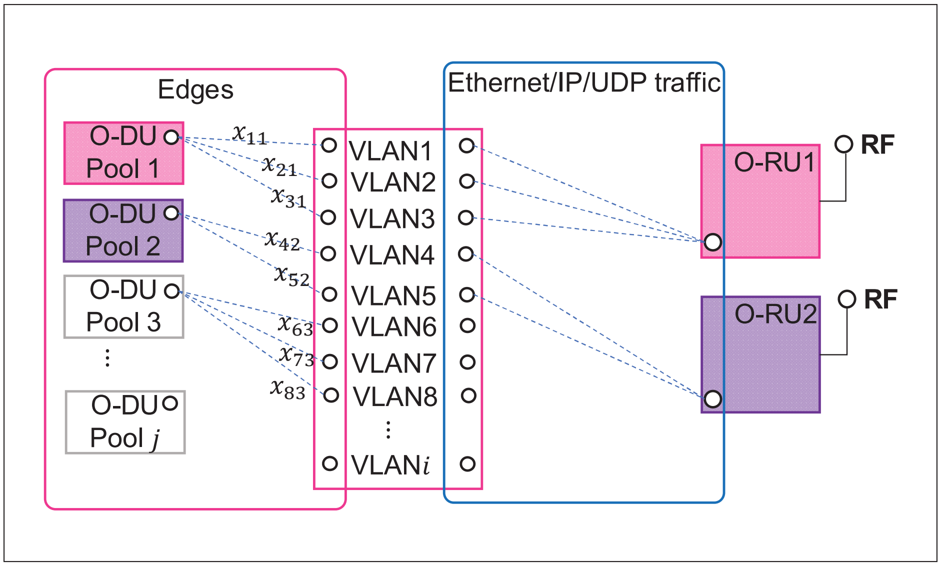

Figure 2.4 Connection map between O-DU pools with VLANs in the BBU pool

by APN names and the corresponding bandwidth for each LoRa gateway. This algorithm fills up the content in TABLE III and TABLE IV. We register the results into the HSS database. MME will look up the HSS database to control LoRa gateways to set up virtual links of the EPS bearer for a dedicated route between the LoRa gateway and the desired PDN.

We design a greedy algorithm [Sudhakar (2019)] to control the LoRa packet arrival rate which indicates the number L of the incoming packets in $\sum_l p_l$. The greedy algorithm firstly starts from the default value, and then increases up according to the objective function. For example, at the arrival rate of 6000 LoRa packets per a second, we calculate the maximum bandwidth of EPS bearers among gateways in the region to serve a massive arrival rate of LoRa packets, and the minimum and the low arrival rate of LoRa packets.

2.2 Open Radio Access Network

2.2.1 System Description

We propose our architecture of O-RAN in Figure 2.4. In our proposed system, we group all O-DUs bound with the same O-RU as an O-DU pool. All the O-DU pools are running on the ODU Pool, a computing resource. The physical resource of O-DU pool can be very flexible to deploy comprehensive 5G computing resources, including Cloud core network, BBU resource or even on the RRU resource, etc. The location of the O-DU depends on the service requirement. For example, an O-DU may be established on the access region on RRU may support the low latency service requirement, while an O-DU in edge resources on BBU is a candidate location to support the superfast broadband service. As per O-RAN specification from the technical specification, the O-DU shall support Ethernet II as Layer 2, including the tagging aspects , untagged Ethernet, single tagged (802.1Q) Ethernet, and dual-tagged (802.1ad) Ethernet [O-RAN (2020b)]. The Ethernet for the O-DU is mandatory, but the choice of tagging leaves for operators to decide, [O-RAN (2020b)]. O-DU shall also support IPv4 as Layer 3 that is mandatory in the O-DU while using IPv4 [O-RAN (2020b)]. When IPv4 is used, and data messages are encapsulated in UDP packets [O-RAN (2020b)]. CTI is an interface in O-RAN to support the resource allocation in the transport networks to transfer U-Plane and C-Plane traffics between O-DU and O-RU by [O-RAN (2020b)]. C-Plane and U-Plane are protocols used for transferring control signals and user data respectively.

In our proposed architecture, we take the single tag VLAN to design our transport network on IPv4 over Ethernet to setup P2P connections between O-DUs in an O-DU pool and an O-RU. Figure 2.4 has also shown an example to integrate services from two vendors into our proposed O-RAN architecture design, e.g. the vendor1 marked in pink color has an O-DU pool 1 and O-RU1, while vendor2 which marked in purple color has O-DU pool 2 and O-RU2. We articulated two problems to enable the coexistence of multiple O-DU pools to transfer packets to O-RUs in the pool. The O-DU pool 1 has reserved three VLANs, and each VLAN that represents a point-to-point connection from the O-RU to the RAT slicing via an O-RU has a different VLAN ID, physical distance, and bandwidth to transfer their packets, while O-DU pool 2 reserved two VLANs as shown in the Figure 2.4. O-DU pools can manage the O-DUs inside to support different RAT slicing for the O-RU by selecting VLANs to forward packets. We assumed O-RUs have their installation in fixed locations. The accumulated delays in each O-DU pool vary because the number of VLAN is the limited resource in the pool. Therefore, the routing problem is arranging the number of VLAN, bandwidth, and physical distance optimally to increase the number of O-DU pools.

Figure 2.5 explains the second problem we proposed about the scheduling mechanism and the delay model for the UDP packet sent from O-DU pool to the O-RU over the IPv4 over the Ethernet network. The O-DU pool at the fronthaul interface uses eCPRI messages to transfer C-Plane control and U-Plane data messages to O-RU in sequentially accumulated delays. We assume at the n slot, and $N-1$ modulated OFDM symbols. Those symbols require the same amount of C-Plane control messages to plot over the phase array antenna. Furthermore, we only consider an O-RU dedicated to serving for a single O-DU pool without retransmission.

After a network transmission delay, all control messages arrived at O-RU fronthaul interface. In the C-Plane, O-RU needs a delay of Tadv_cp_dl in the downlink to translate the control messages' parameters. Then O-DU pool initiates its first OFDM symbol ready to send over the U-Plane. U-Plane uses IP over the Ethernet network to transfer data, while the OFDM modulated user data is carried over the UDP protocol encapsulated in the UDP/IP protocol. As we have articulated the problem in section II, the UDP size limitation may not contain OFDM symbols' full size. So, O-DU instant at the fronthaul interface may fragment the OFDM symbol into multiple small packet sizes to fit the UDP payload. The example is shown in the Figure 2.5, an O-DU pool fragmented the first OFDM symbol into four pieces to load into four UDP payloads, which requires four to be transferred over the Ethernet network, while the second OFDM symbol requires two IP packets. The problem is finding out the load rate to fill up bits from an OFDM symbol into the UDP payload to control the UDP packets' number.

Two problems have to be addressed, namely the routing problem and the packet scheduling problem. The routing problem is associating the optimal routes from an O-DU pool to a VLAN link dedicated by this VLAN ID and bandwidth, and the UDP packet scheduling problem is to minimize system response time among O-DU pools in the O-DU pool [Mohamed (2019)]. We solved the problems to determine the globally optimal set of the combination among routing, packet sizes and bandwidth to assign to the O-DU pool. We also apply the greedy algorithm to approximate the routing, packet sizes, and bandwidth by an optimal local value implemented by the first candidate fit principle because of the solution's complexity.

2.2.2 O-DU Pool Routing Model

Figure 2.4 presents a mapping for the connections between O-DU pools and VLANs created in the O-DU pool. There is i VLANs and j O-DU pools. We define x_{ij}, which is a decision variable, indicates that the O-DU pool 1 associates its links of VLANs when $x_{ij} = 1$; otherwise when $x_{ij} = 0$ [Chen (2015)]. For example, in Figure 2.4, VLAN1, VLAN2 and VLAN3 associated with the O-DU pool 1, and we denote them x_{11}, x_{21}, and x_{31} respectively.

We assume that a VLAN can only be associated to an O-DU pool, represented as:

$$\sum_{\forall j} x_{ij} = 1. \tag{2.12}$$

The connection constraint that an O-DU pool has to be associated with at least one VLAN to route the traffic and less than K_j, the maximum number of VLANs for the j O-DU pool, formulated by:

$$1 \leq \sum_{\forall i} x_{ij} \leq K_j. \tag{2.13}$$

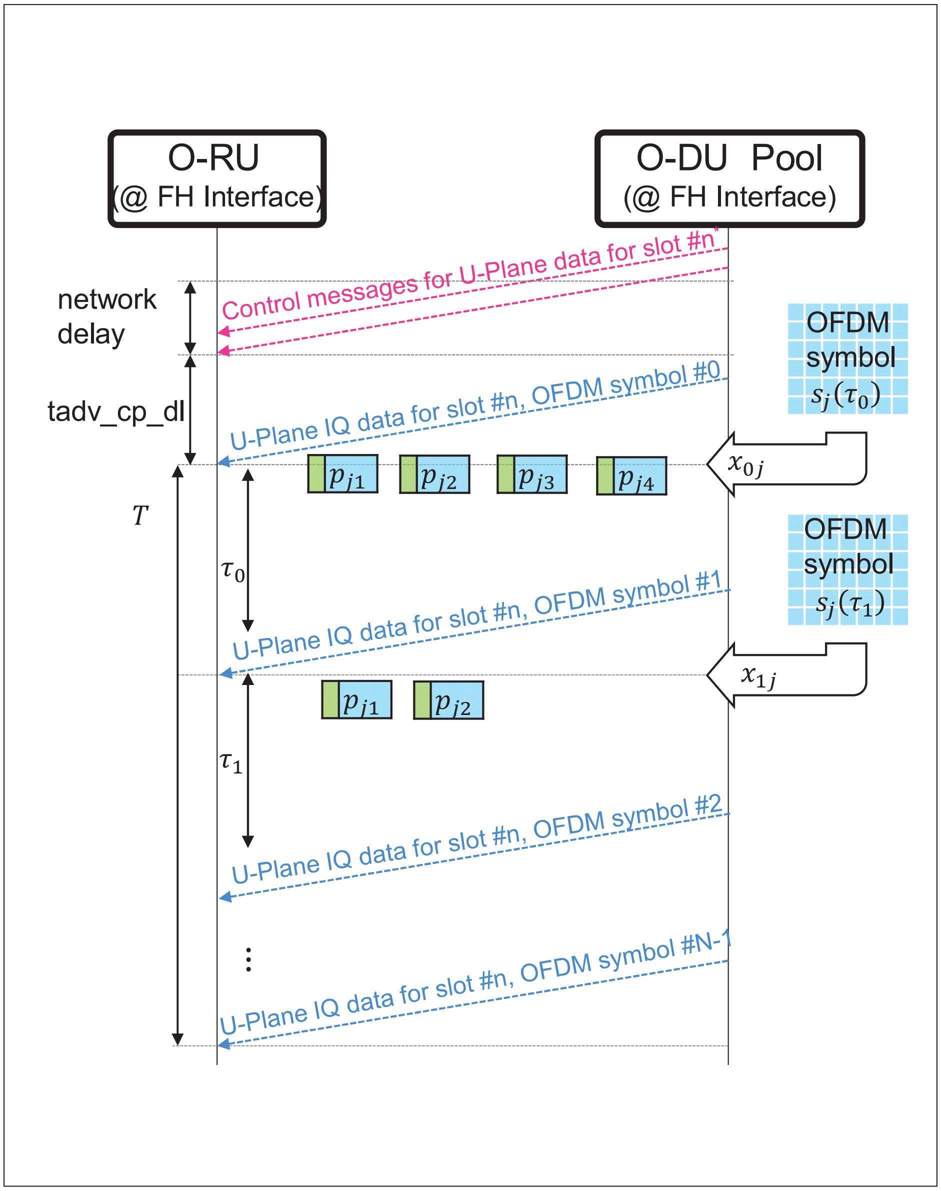

Figure 2.5 The UDP packet mapping in the delay between O-DU pool and O-RU

2.2.3 O-DU and O-RU Packet Scheduling Model

We formulate the problem by a set of fragmented UDP packets. The k th packet $p_{jk} \in \mathbb{Z}^{+}$ of the j O-DU pool such that $0 \leq p_{jk} \leq 1550 Bytes$, which is fragmented from an OFDM symbol

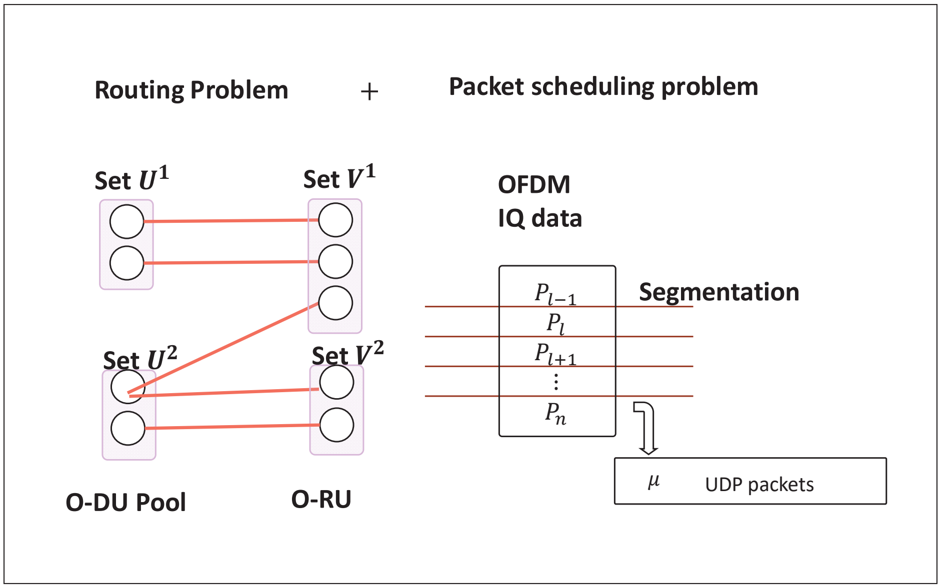

Figure 2.6 Joint RPS model for O-RAN

$s_j(\tau)$ during the slot τ of the j O-DU pool, as:

$$\sum_k p_{jk} \geq s_j(\tau), \ \forall j. \tag{2.14}$$

$F(\cdot)$ is a function to map the bandwidth of a dedicated link x_{ij}, formulated by:

$$F(x_{ij}) = \frac{x_{ij} \sum_k p_{jk}}{\tau}. \tag{2.15}$$

By $M/M/1$ queueing theory, the expected waiting time for 14 slots of τ of OFDM symbols should be less than T, as:

$$\frac{1}{B_j} \sum_i \sum_j \frac{F(x_{ij})}{B(x_{ij}) - F(x_{ij})} \leq T. \tag{2.16}$$

2.2.4 Objective Functions

2.2.4.1 eMBB mapping problem

The eMBB service demands superfast bandwidth and the excellent quality for the application. The objective function is to maximize the total bandwidth by joint routing and packet scheduling model presented in Figure 2.6, as:

$$\text{Max.} \quad \sum_{i,j} B(x_{ij}), \tag{2.17}$$

where it subjects to constraints of (2.12) (2.13) (2.16).

2.2.4.2 mMTC mapping problem

The mMTC service requires a very large number of connections with limited resources in the fronthaul network. The objective is to maximize the number of connections by joint routing and packet scheduling model presented in Figure 2.6, as:

$$\text{Max.} \quad \sum_{i,j} x_{ij}, \tag{2.18}$$

where it subjects to constraints of (2.12) (2.13).

2.2.4.3 URLLC service mapping problem

The URLLC service in the RAT slicing requires the minimal latency. Therfore, the objective function is to minimize the delay of each O-DU pools by joint routing and packet scheduling model presented in Figure 2.6, as

$$\underset{x_{ij}}{\text{Min.}} \quad \frac{x_{ij} \sum_k p_{jk} - s_j}{B(x_{ij})}, \tag{2.19}$$

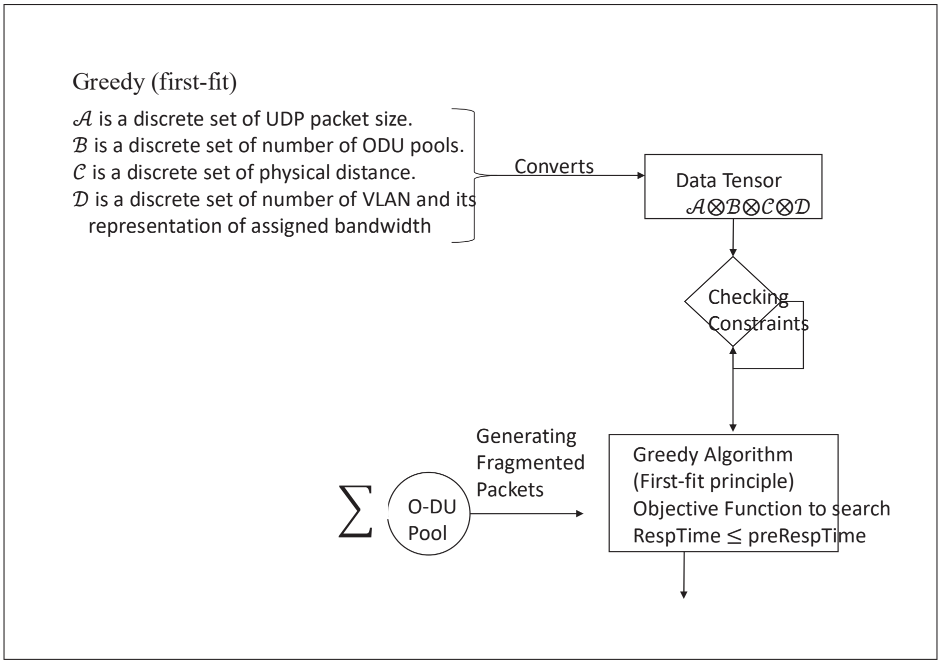

Figure 2.7 block diagram of greedy algorithm

where it subjects to constraints of (2.12) (2.13) (2.14) (2.15) (2.16) .

2.2.5 Algorithmic Solutions

To solve three optimization problems (2.17) , (2.18), and (2.19), we design two algorithms: a greedy in Figure 2.7 and a DP algorithm in Figure 2.8. Algorithm 2.1 is a greedy method to search in a four-dimensional matrix data structure generated in generateMatrix function. We use the tensor product of vectors in each axis of the matrix from VLANs, bandwidth, UDP packet size to distance. As the number of O-DU pools increases, the matrix becomes more complicated in combinations. The checkConstraints function has a for-loop to iterate the O-DU pools among all edge resources. By checking constraints, we iterate every item in the matrix. If all constraints are satisfied, we batch the data and use the objective function to calculate the response time based on the URLLC service. It is a first-fit greedy algorithm. The algorithm searches the data set that we batched from the checkContrains function. It starts from the beginning of the dataset to compare the current minimum response time and the previous minimum response time. We

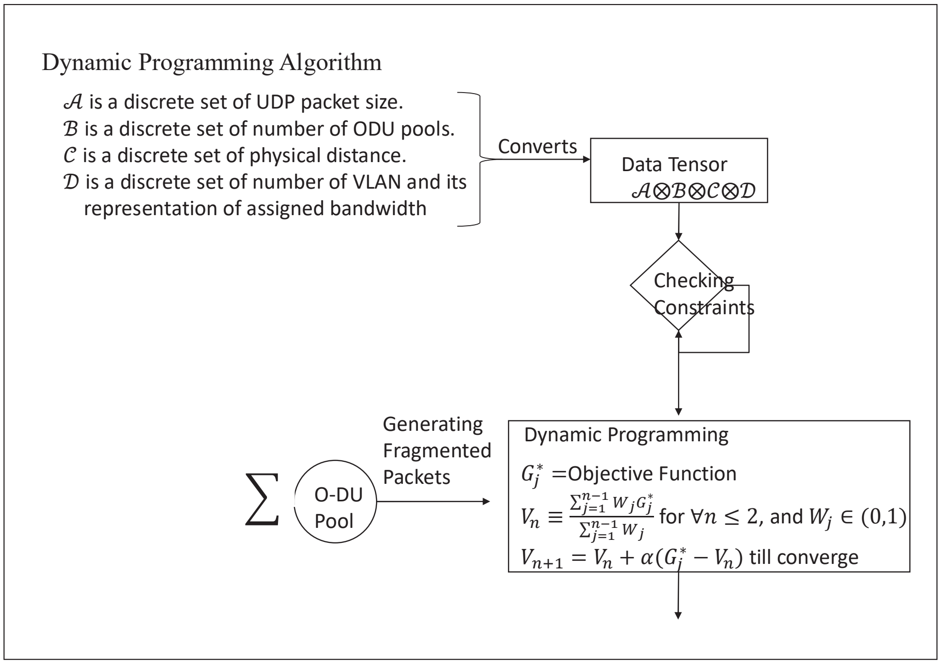

Figure 2.8 block diagram of DP algorithm

design the greedy algorithm in the main function to find the approximately minimum delay. The greedy algorithm stops until it finds the first-fit minimum value from the data set.

Algorithm 2.2 is a DP method that iterates a recursive Bellman equation until it converges. α is a scaling parameter to control the step of the heuristic function $G_n^* - V_n$. We define G_j^* as the minimum response time by searching the optimal connections x_{ij}^*, packet sizes p_{jk}^* and bandwidthes $B^*(x_{ij})$ which are assigned to each of O-DUs inside the O-DU pool j. the j th O-DU pool . V_n is a normalized weighted sum of the minimum response time G_j^* from 1 to the $n-1$, where W_j is a weighting parameter of a real number between open interval of 0 and 1.

Algorithm 2.1 Greedy Algorithm

```
Input: Number of O-DU pools
Output: Minimum Reponse Time

Function generateMatrix():
    Matrix = oduInstNum ⊗ vlanBWSet ⊗ udpSizeSet ⊗ distance;
    return Matrix;
Function checkConstraints(Matrix):
    for each num in Matrix.oduInstNum do
        for each vlanBW and updSize and distance in Matrix do
            Check constrons;
            Fragment the OFDM symbol;
            Mapping with UDP payload ;
            Mapping with VLAN bandwidth;
            for Select VLAN do
                Objective function to calculate delay time;
            end for
        end for
        return Response time matrix;
    end for
Function Main:
    /* First fit greedy method                                   */
    Matrix = generateMatrix();
    resultMatrix = checkConstraints(Matrix);
    for item in resultMatrix do
        if item.currentRespTime ≤ item.previousRespTime then
            return minimal first-fit response time;
            break;
        end if
    end for
return
```

Algorithm 2.2 Dynamic Programming Algorithm

Input: Bandwidth, Connection, Packet size
Output: Minimum Response Time

1 Initializing $\alpha \in \mathbb{R}$ s.t. $\alpha \in (0, 1)$.
2 Iterating the recursive function until it converges,

$$V_{n+1} = V_n + \alpha(G_n^* - V_n);$$

where

$$V_n \equiv \frac{\sum_{j=1}^{n-1} W_j G_j^*}{\sum_{j=1}^{n-1} W_j} \text{ for } \forall n \leq 2, \text{ and } W_j \in (0, 1);$$

3 and assign to G_j^* by searching the optimal value of the objective function for each O-DU pool j for URLLC service.

$$G_j^* \equiv \frac{x_{ij}^* \sum_k p_{jk}^* - s_j}{B^*(x_{ij})};$$

CHAPTER 3

NUMERICAL RESULTS

In this chapter, we present the simulation results for LoRaWAN-EPC integration and O-RAN problem. At first, we present the environmental settings, then we discuss the numerical results of our proposed solutions.

3.1 LoRaWAN-EPC integration network simulation

3.1.1 Settings

Our simulation includes 32 gateways in three regions. Two regions u^1 and u^2 have 11 gateways each, and u^3 has 10 gateways. There are four LoRa network servers which require four gateways to be active at any moment of time. The remaining the gateways are standby. Each route between a gateway and a network server has a dedicated bearer service rate.

Each LoRa gateway has predefined all APN names of the LoRa network servers. Each route between gateway and network server has a physical distance. To simplify the simulation, we define a fixed UDP size of 1500 Bytes. The maximum loading rate is the maximum packet size divided by the unit time to load the LoRa packets into UDP packets. The rate of LoRa packets that sensors are sending under the same region to gateways varies from 100 LoRa packets per second up to 10000 LoRa packets per second. UDP generating rates are 2 Mbps, 4 Mbps, 6 Mbps, and 10 Mbps respectively. In Table 3.1, the gateways that connect to the network server 1 according to our algorithm to have the indexes of indexes 2, 8, and 10 in region 1. Their corresponding EPS bearer bandwidths are respectively 10 Mbps, 6 Mbps, and 4 Mbps, in Table 3.2. So the maximum bandwidth of 10 Mbps is used the massive flow of LoRa and 4 Mbps of the bearer established for the small flow of LoRa.

Table 3.1 Connection table of gateways for APN names

Index	LoRa gateway	Region 1	Region 2	Region 3
1	**Gateway 1**	APN 3	APN 2	APN 2
2	**Gateway 2**	APN 1	APN 4	APN 3
3	**Gateway 3**	APN 2	APN 1	APN 4
4	**Gateway 4**	APN 4	APN 3	APN 1
5	**Gateway 5**	APN 2	APN 3	APN 1
6	**Gateway 6**	APN 2	APN 3	APN 4
7	**Gateway 6**	APN 4	APN 1	APN 2
8	**Gateway 8**	APN 1	APN 4	APN 4
9	**Gateway 9**	APN 4	APN 2	APN 2
10	**Gateway 10**	APN 1	APN 2	APN 3
11	**Gateway 11**	APN 4	APN 1	

Table 3.2 Bandwidth table of gateways for EPS bearers

Index	Region 1	Region 2	Region 3
1	4 Mbps	2 Mbps	6 Mbps
2	10 Mbps	4 Mbps	6 Mbps
3	10 Mbps	4 Mbps	6 Mbps
4	10 Mbps	2 Mbps	2 Mbps
5	2 Mbps	6 Mbps	6 Mbps
6	4 Mbps	6 Mbps	2 Mbps
7	2 Mbps	4 Mbps	10 Mbps
8	6 Mbps	4 Mbps	6 Mbps
9	2 Mbps	10 Mbps	4 Mbps
10	4 Mbps	2 Mbps	6 Mbps
11	10 Mbps	6 Mbps	

3.1.2 Results

We compare our greedy algorithm with a baseline algorithm that randomly selects four gateways connecting to network servers, and the gateways will call their default bandwidth of the EPS bearer in the first simulation. Figure 3.1 shows the average response time resulting from the baseline algorithm for three regions, which increases according to LoRa packets rate. We use the first four gateways from all regions. In region 1, the average response time is the lowest

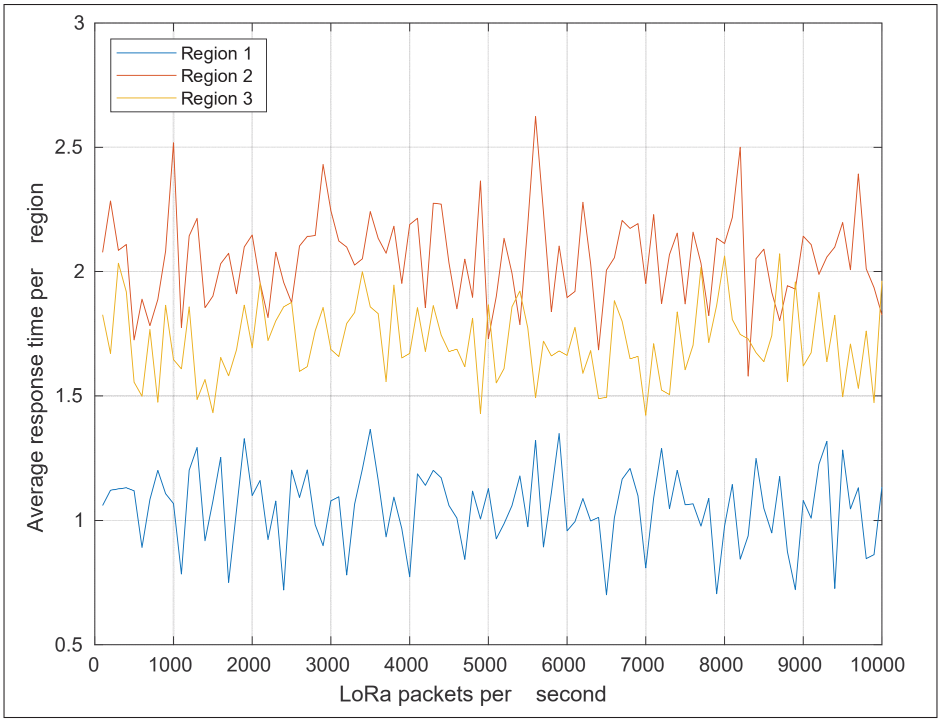

Figure 3.1 The result of the response time in three regions where LoRa gateways in each region randomly select EPS bearers among all traffic of arrival LoRa packets

among all regions, because the UDP service rate of the EPS bearer holds high bandwidth to access network servers. Region 3 has a moderate UDP service rate, and region 2 has a lower service rate. The fluctuation is due to the random LoRa packet size that stays in the range from 11 bytes to 250 bytes. LoRa packet requires 11 bytes to transfer the MAC command information, and the LoRa packet can extend up to 250 bytes to transfer data information. However, if we chose gateways with the highest bandwidth of its EPS bearer, Figure 3.2 shows the response time of all gateways reaches 2.05 ms for any arrival rate of the LoRa packets.

Our proposed algorithm can find out the optimal routing, and we calculate the response delay on LoRa gateway by applying the various EPS bearers based on the arrival rate of LoRa packets and compare the results. Our simulation shows our algorithm can reduce 200 ms of average delay by selecting the policy of optimal routing and the scheduling mechanism to forward LoRa packets over the route in the EPC resource. The average response times shown in Figure 3.3

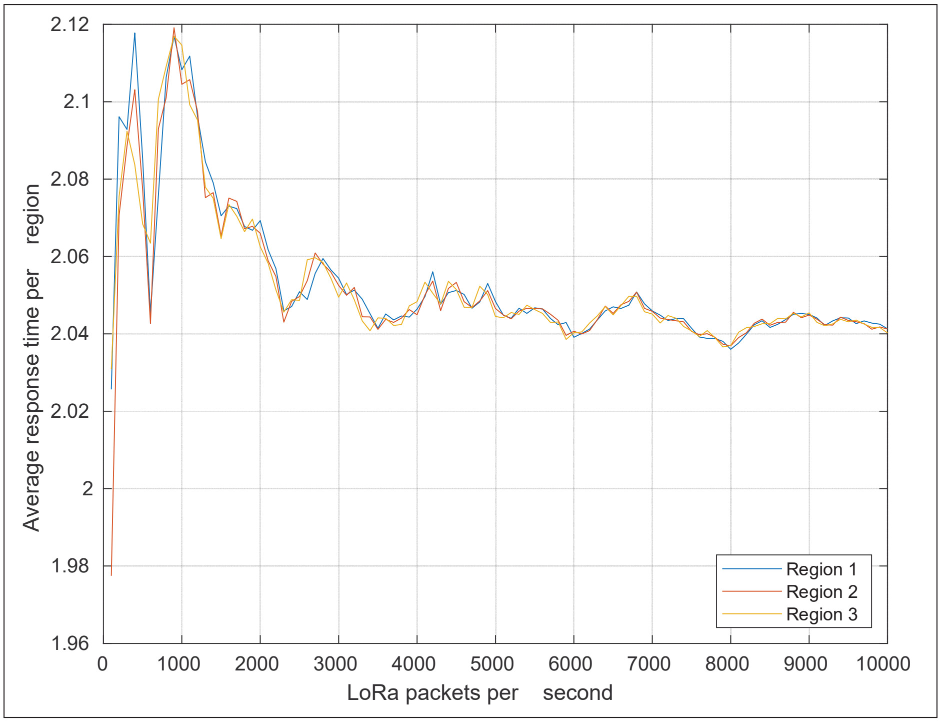

Figure 3.2 The result of the response time in three regions where LoRa gateways in each region always select maximum bandwidth of EPS bearers

are very similar among all regions. It is because instead of selecting a random set of gateways, we chose gateways with the lowest bandwidth of EPS bearer, when the arrival rate of the LoRa packet is less than 2000 packets per second, and the gateways having the highest bandwidth, when the arrival rate is above 2000 packets per second. The result shows that all curves fluctuate around to an average of 1.64 ms, when the arrival rate is under 2000 packets per second. Finally, all curves converge to the upper bound of 2 ms because of the limitation of the fixed UDP packet size. Figure 3.4 shows the average response time we select a minimum EPS bearer bandwidth, when the arrival rate of LoRa packets is under 6000 packets per second. As shown, all the response times are at 1.64 ms on average, when the arrival rate is under 6000 packets per second, and the response time reaches 1.8 ms, when there are more than 6000 packets per second.

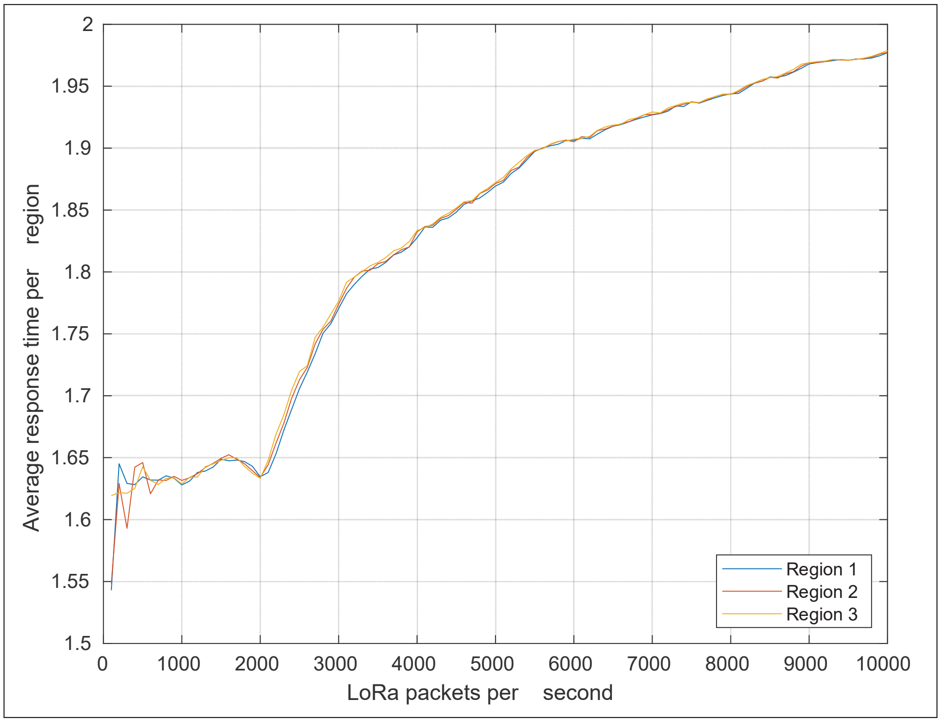

Figure 3.3 The result of the response time in three regions where LoRa gateways in each region select minimum bandwidth of EPS bearers below and above 2000 pps

3.2 O-RAN simulation

3.2.1 Settings

In this simulation, we simulated the O-DU pool to apply 8 O-DU pools. Each O-DU pool contains at least one or more VNF of O-DU, requiring a VLAN to route the UDP packet over a distance and bandwidth in the requirement from 5G RAT slicing. So it is a challenging problem to simulate because we need to construct a four-dimensional matrix of distance, VLANs with different bandwidths associated with each O-DU pool, UDP packet size and O-DU pools. For simplicity, we set that Maximum VLAN numbers in the O-DU pool are less and equal to 50. One O-DU pool can associate a maximum of 3 VLANs that are assigned with different bandwidths from a set of 50 Mbps, 100 Mbps and 150 Mbps. The distance is less and equal to the minimum required distance. The total bandwidth upper limit in the O-DU pool is less and equal to 1 Gpbs

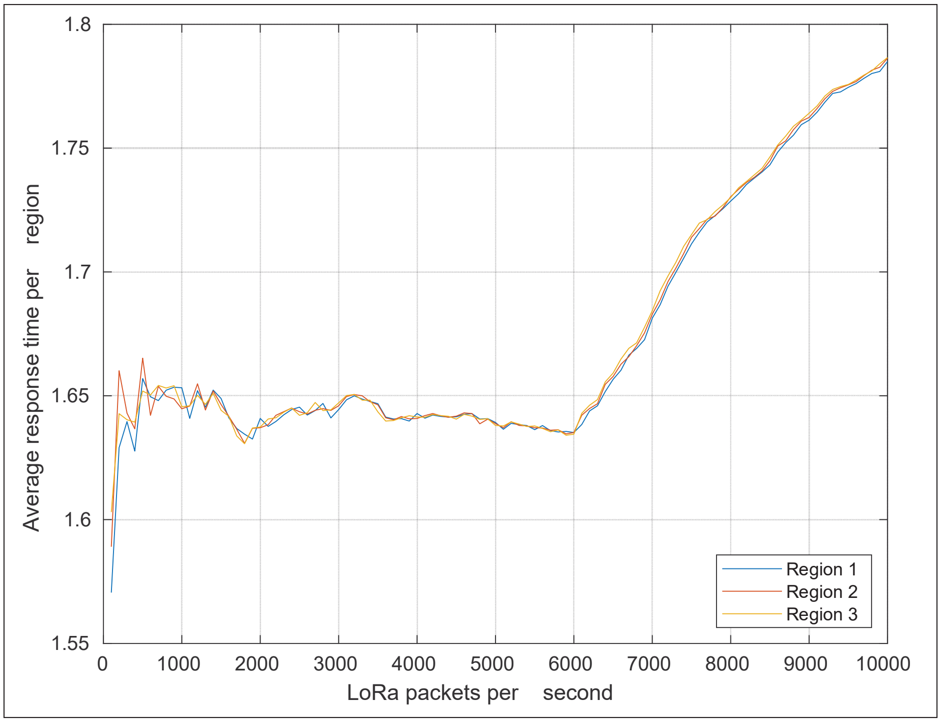

Figure 3.4 The result of the response time in three regions where LoRa gateways in each region select minimum bandwidth of EPS bearers below and above 6000 pps

physical port. An OFDM symbol can be fragmented into a maximum number of 12 packets. The O-DU pool has four loading rates for the UDP payload of 12400 bits per millisecond, 11000, 10000, and 9000 bits per millisecond.

To validate Algorithm 2.1, we set up a single O-DU pool associated with three VLANs of the assigned bandwidth 50 Mbps, 100 Mbps, and 150 Mbps at distances 50m, 1000 m 5000 m. O-DU pool allows the O-DUs to classify their fragmented packets over three VLAN to forward the UDP packets. The VLAN classification principle has the mechanism to map the number of fragmented packets from the OFDM symbol with the UDP loading rate that controls the UDP payload size for τ. We set up the $\tau = 1ms$. The default UDP payload size is 1550 Bytes, which is 12400 Bits. If a VLAN route of 50 Mbps is selected, the O-DU pool may transmit maximal four packets. The bandwidth 100 Mbps may allow a maximum of eight packets, while 150 Mbps for 12 packets. For example, during the τ period, the O-DU pool loads the UDP packet

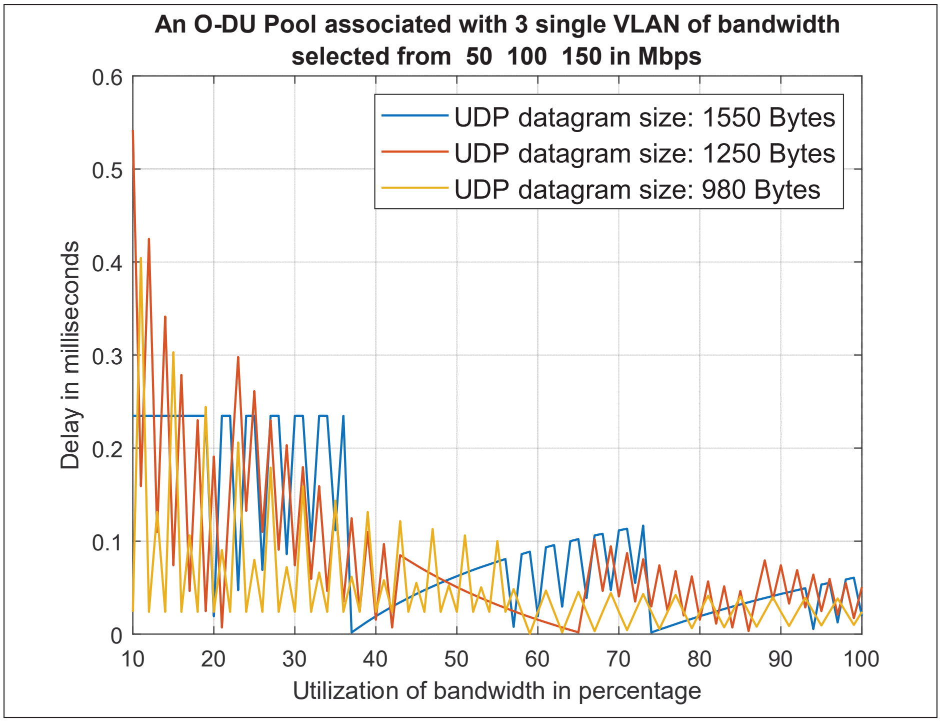

Figure 3.5 An O-RU instance generates UDP size of 1550 Bytes and 1375 Bytes and 1250 Bytes over the selective three VLANs assigned with 50 100 or 150 Mbps

with a maximum rate of 12400 Bits per millisecond. For three packets (e.g. 7800 Bits, 9800 Bits, 11520 Bits) during the τ, O-DU pool selects the 50 Mbps route of VLAN to forward. The delay time for the O-DU pool is 0.4 milliseconds. The simulation of the VLAN classification mechanism in Fig. 3.5 for three O-DU dwelling in the single O-DU pool at 3 UDP loading rate can fill 1550 Bytes of payload, 1250 Byte and 980 Bytes of payload size. Fig. 3.5 interprets as the increase of the utilization of the VLAN bandwidth, the delay varies from three UDP payload sizes.

3.2.2 Results

The blue line in the Fig. 3.6 is drawn by the numerical result that finds out the optimal global value by DP algorithm in the matrix of O-DU pools, UDP packet size, and bandwidth for the associated VLAN. By comparing the solution's baseline, we implemented a greedy algorithm that approximates the optimal value by the first fit principle. From the pattern we learned from the single O-DU pool, we can iterate the four-dimensional matrix in sequential order, the greedy algorithm stops until it reaches its first minimum value of accumulated delay among 8 O-DU pools. The red line is drawn by the numerical result from the greedy algorithm. It interprets that the greedy algorithm would well approximate the solution in the lightweight and fast computing resources.

As the interpretation from Fig. 3.6, the average difference of between DP algorithm and greedy algorithm is 1.1 ms, as O-DU pools increased from 1 to 8. The system has the minimum 0.1586 ms difference in the accumulated response time when single O-DU pool is launched. And the error of the approximation from greedy method to DP method is increasing and up to 1.604 ms, while 8 O-DU pools are launched to operate in the coexisting manner by sharing the VLANs, Bandwidthes in the system. However, compared with the complexity $O(n^2 \log n)$ of DP method, our greedy algorithm has complexity of $O(\log n)$ in the first-fit principle. Since the complexity of searching reduced by n^2 time, greedy algorithm is a good approximation method for our system.

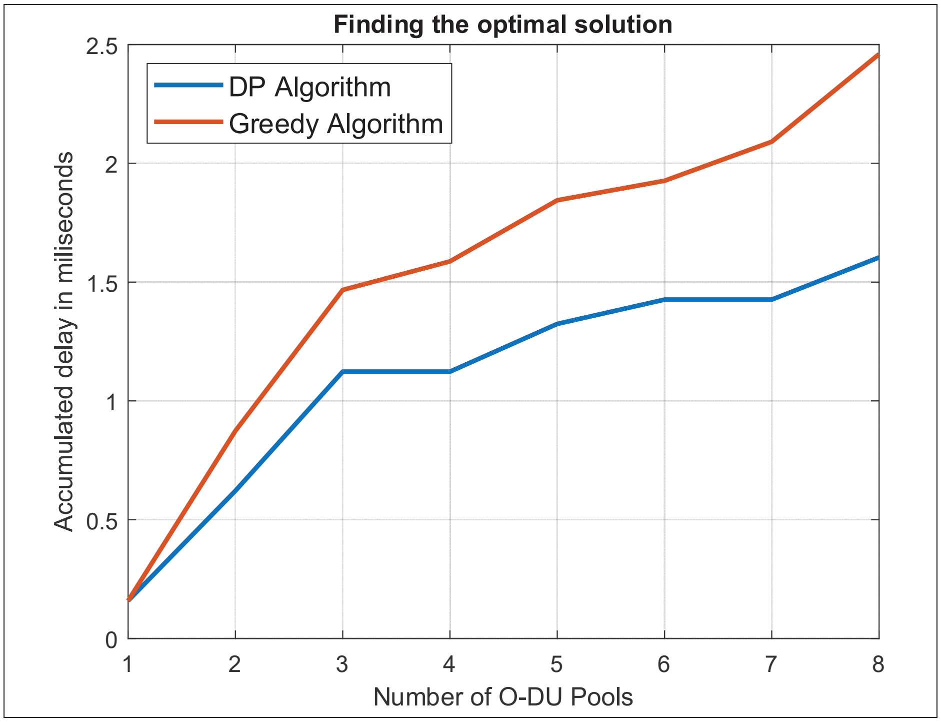

Figure 3.6 Comparing the approximation of greedy algorithm with the optimal values of DP algorithm

CONCLUSION AND RECOMMENDATIONS

In this thesis, we have presented two routing and packet scheduling problems. The first problem address the integration of the multiple LoRaWANs to use the existing core of 4G/LTE and GTP-u tunnels of EPS bearers in the EPC resource. We formulated the problems of dedicated routes, optimal routing and scheduling of LoRa packets, when accessing the EPC resource. Through simulation results, we showed the optimal policies to select routes in the EPC resource can reduce the overall delay of average response time.

The second problem is to optimize routing and scheduling between O-DU pools and O-RUs to meet 5G requirements of minimal costs. We design a greedy algorithm to compare the difference between the optimal value and to approximate optimal value achieved by DP algorithm.

In the future, we will apply machine learning techniques to analyze computational data to predict the system policy. We will implement our proposed routing and packet scheduling models for a 5G testbed in an ongoing research project in collaboration with Ciena Corp within the ENCQOR framework. We will also design Reinforcement Learning algorithms for our system and extend our applications to involve 5G beamforming.

APPENDIX I

ARTICLES PUBLISHED IN CONFERENCES

This thesis is related two conference papers. The first paper entitled "Routing and Packet Scheduling in LoRaWANs-EPC Integration Network" has been presented in the IEEE GLOBECOM 2020 conference in Taipei (Taiwan) in December 2020 [Zhang (2020)]. The second paper entitled "Routing and Packet Scheduling For Virtualized Disaggregate Functions in 5G O-RAN Fronthaul" has been submitted in October 2020 to the conference of IEEE ICC 2021 which will take place in Montreal (Canada).

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