O-RAN Near-RT RIC-Based Multi-RAT Bidirectional Traffic Steering between 5G and WiFi

Minseo Kim
Department of Computer Science and Engineering
POSTECH
Pohang, Republic of Korea
dhksfy41@postech.ac.kr

Hwangjun Song
Department of Computer Science and Engineering
POSTECH
Pohang, Republic of Korea
hwangjun@postech.ac.kr

***Abstract*—This work presents a system for bidirectional traffic steering between 5G and WiFi using the Open-RAN (O-RAN) Near-Real-Time RAN Intelligent Controller (Near-RT RIC) framework. Most of existing systems support unidirectional steering from 5G to WiFi, and no explicit mechanism has been proposed to automatically return the UE to 5G when WiFi channel quality deteriorates significantly. The proposed system addresses this limitation by managing both 5G and WiFi as E2 Nodes under a unified Near-RT RIC. The proposed E2 Adapter bridges the Near-RT RIC and a WiFi SDN controller, and the proposed xApp observes and controls the WiFi domain through standard E2 interfaces. The xApp continuously monitors channel quality across both access technologies and autonomously switches the UE between 5G and WiFi based on real-time measurements of RSSI and retry rates. The system is performed on a real testbed comprising an OpenAirInterface (OAI) 5G standalone (SA) gNB with USRP X410, FlexRIC as the Near-RT RIC, and ONOS as the SDN controller. Experimental results show that the proposed system correctly detects RSSI degradation and channel congestion as steering triggers and maintains throughput continuity across all transitions. Furthermore, the end-to-end control loop latency clearly satisfies the O-RAN Near-RT RIC requirement of 10 ms.**

***Index Terms*—O-RAN; Multi-RAT; Traffic Steering; 5G; WiFi; closed-loop control**

I. Introduction

Wireless access networks in enterprise campuses, smart factories, and dense urban environments are increasingly deploying 5G and WiFi as overlapping access technologies for the same set of devices. When a single access technology is exclusively utilized, its inherent limitations are directly exposed to the user. WiFi links, for instance, are vulnerable to signal attenuation as devices move away from the access point and are prone to throughput instability under conditions of network channel congestion. Conversely, exclusive reliance on 5G neglects the potential benefits of WiFi, which can provide high-throughput, and cost-efficient connectivity in localized environments. The complementary strengths of these technologies can only be fully exploited if traffic is dynamically steered between them in response to real-time variations in channel quality and network load. This necessitates the design of a network-level control architecture capable of continuously observing both access technologies and enforcing steering decisions through a unified automation loop.

Prior work on multi-RAT integration has addressed aspects of the traffic steering problem; however most of existing systems exhibit two fundamental limitations. First, steering decisions are typically unidirectional. Traffic may be offloaded from 5G to WiFi when 5G capacity is constrained, but once the UE is transitioned to WiFi, it remains there irrespective of subsequent changes in WiFi channel quality. For example, a UE offloaded to WiFi may lose connectivity as the signal weakens with distance from the AP, or experience degraded performance when the channel becomes congested with competing traffic [1], [2]. In either scenario, existing systems provide no explicit mechanism to detect WiFi channel degradation and automatically return the UE to 5G. Second, 5G and WiFi are managed by separate control planes that do not share state information or policy with each other. As a result, an operator who wants to make a joint steering decision across both technologies must coordinate them manually, since no common interface exists to enforce such decisions. This lack of coordination means that throughput continuity across the two access technologies cannot be guaranteed, and that operators cannot exercise unified control over the multi-RAT environment. The O-RAN RIC framework addresses this gap by providing a foundational architecture that enables unified, policy-driven control over multiple access technologies [3]. Its Near-RT RIC hosts xApps that observe network state through standardized E2 interfaces and enforce per-UE decisions within a closed control loop. Operator intent is expressed as policies and distributed to the Near-RT RIC from the Non-Real-Time RIC (Non-RT RIC) [4], [5]. However, the current E2 ecosystem encompasses only 3GPP RAN nodes, and no standard mechanism exists for an xApp to observe or control WiFi access points. Therefore, WiFi cannot participate in the closed control loop provided by the RIC, and any recovery from WiFi channel degradation must rely on device-side logic [6]–[8], rather than network-level automation.

This work addresses both limitations by proposing a system that extends RIC-based control to WiFi. The key idea is to register the WiFi control plane to the Near-RT RIC as an E2 Node. Once WiFi participates in the same E2 ecosystem as 5G, the Near-RT RIC can observe and control both access technologies within a single closed control loop, based on common operator-defined policies.

979-8-3195-0167-7/26/$31.00 ©2026 IEEE

This work makes the following contributions:

- Proposing an O-RAN RIC-based system for multi-RAT bidirectional traffic steering, in which 5G and WiFi are managed as E2 Nodes under a single Near-RT RIC. The proposed xApp continuously monitors the channel quality of both access technologies and switches the UE between 5G and WiFi based on real-time channel measurements.
- Designing and implementing the proposed E2 Adapter that connects the WiFi control plane to the Near-RT RIC as an E2 Node. The E2 adapter enables the xApp to observe WiFi channel conditions and enforce steering decisions on the WiFi domain through standard E2 interfaces.
- Presenting a policy-aware steering mechanism in which operator-defined steering parameters are distributed from the Non-RT RIC to the xApp. This design allows the operator to adjust the steering behavior through policy updates.
- Validating the proposed system on a real testbed built on an OpenAirInterface (OAI) [9] 5G SA gNB with USRP X410, FlexRIC [10] as the Near-RT RIC, and ONOS [11] as the SDN controller. The system correctly detects WiFi channel degradation and maintains throughput continuity across bidirectional steering transitions.

The remainder of this work is organized as follows. Section II reviews the O-RAN RIC architecture and existing approaches to multi-RAT traffic steering between 5G and WiFi. Section III describes the proposed bidirectional traffic steering system. Section IV presents the policy-aware steering design. Section V reports the experimental results on a real testbed. Finally, Section VI provides the conclusion.

II. Background and Related Work

In this section, we first review the O-RAN RIC architecture and existing approaches to multi-RAT steering between 5G and WiFi, and identify the limitations that motivate the present work.

A. O-RAN RIC Architecture

The O-RAN ALLIANCE [12] specifies a two-tier intelligent controller architecture composed of a Non-RT RIC and a Near-RT RIC. The Non-RT RIC is hosted within the Service Management and Orchestration (SMO) framework, operates on control loops exceeding 1 s, and hosts rApps for policy generation, model training, and long-horizon optimization. The Near-RT RIC operates within the 10 ms to 1 s control loop range and hosts xApps that perform per-UE or per-cell decisions based on real-time measurements collected from the RAN nodes. The two tiers are connected through the A1 interface, which carries policies (A1-P), enrichment information (A1-EI), and machine learning model updates (A1-ML) from the Non-RT RIC to the Near-RT RIC.

The Near-RT RIC interacts with the RAN nodes over the E2 interface. On the RAN side, the endpoint of the E2 interface is an E2 Node, which the O-RAN specifications currently define as a disaggregated 3GPP RAN entity, specifically an O-RAN gNodeB (O-gNB), O-RAN Central Unit (O-CU), O-RAN Distributed Unit (O-DU), or O-RAN eNodeB (O-eNB). Each E2 Node advertises its supported capabilities to the Near-RT RIC through RAN Functions, and the messages exchanged over the E2 interface are structured according to the corresponding E2 service models (E2SM). Four E2SMs are currently defined by the O-RAN ALLIANCE [13]. Key Performance Measurement (KPM) E2SM carries periodic measurement reports from the E2 Node to the Near-RT RIC. The RAN Control (RC) E2SM carries control actions from the Near-RT RIC to the E2 Node. The Network Interface (NI) E2SM exposes signaling messages exchanged over standard 3GPP RAN interfaces. The Cell Configuration and Control (CCC) E2SM supports cell-level configuration. Each E2SM defines two types of message exchange: E2 indication messages, used by E2 Nodes to report measurements or events to the Near-RT RIC, and E2 control messages, used by the Near-RT RIC to send control actions to the E2 Nodes. The E2 interface relies on standard transport and encoding mechanisms, with Stream Control Transmission Protocol (SCTP) used for transport and Abstract Syntax Notation One Packed Encoding Rules (ASN.1 PER) for message encoding and decoding. These mechanisms are not inherently restricted to 3GPP RAN entities, and any node that conforms to the E2SM specification can in principle register as an E2 Node. The present work builds on this property to expose a non-3GPP WiFi domain to Near-RT RIC through a customized E2 Node.

B. Multi-RAT Traffic Steering

The primary standardized mechanism for integrating 5G and WiFi is the ATSSS [14], which allows a UE to use both 5G and WiFi simultaneously through the 5G core. However, ATSSS has two limitations in an operator-controlled setting. First, the steering function runs on the UE side, and therefore only works on devices that support the ATSSS. Legacy devices that do not support it are excluded from any steering decision, regardless of the operator's intent. Second, ATSSS has no visibility into WiFi-side conditions, such as channel quality or AP load. WiFi is treated simply as a data path, therefore, the operator cannot observe or act on the WiFi side when making steering decisions. To address this visibility gap, SDN-based controllers such as ONOS provide direct control over the WiFi infrastructure. However, these systems operate independently of the 5G RAN and do not share a common control plane with it. Any policy that depends on both the 5G and WiFi states must therefore be managed separately across two disconnected control planes with no common interface.

Prior studies on multi-RAT traffic steering have explored learning-based approaches. DQN [15] and HRL [16] demonstrate throughput and latency improvements over heuristic baselines, while COHERE [17] incorporates access-node load and link delay alongside RSSI to improve handover quality. However, these studies were evaluated exclusively in simulations and did not address the closed-loop control requirements imposed by the O-RAN specifications. Furthermore, none of these approaches provides a mechanism to detect WiFi channel

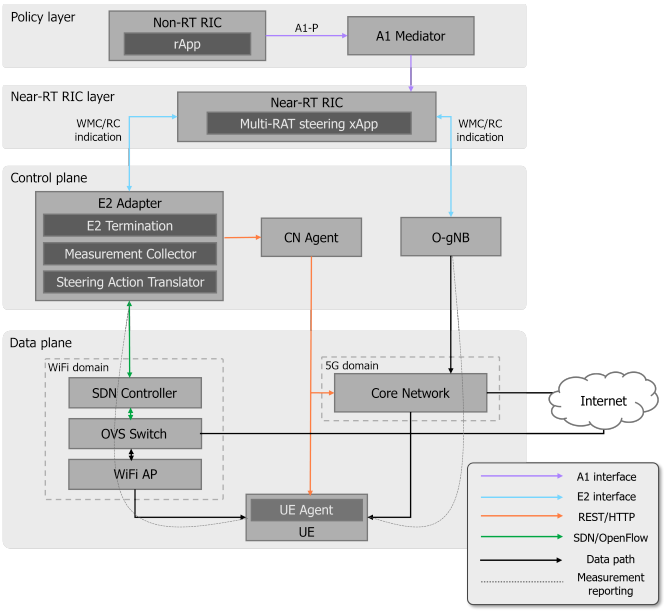


Fig. 1. Overall system architecture of the proposed O-RAN RIC-based multi-RAT bidirectional traffic steering.

degradation and trigger a return to 5G. Therefore, throughput continuity is not guaranteed when channel conditions deteriorate after a UE has been offloaded to WiFi. More recent studies have explored multi-RAT steering within an O-RAN architecture. Kefalas et al. proposed a system that employs LSTM-based demand forecasting within an O-RAN xApp to activate WiFi when 5G capacity is projected to be exceeded, and to restore 5G when demand falls within capacity [18]. However, steering decisions are based solely on traffic demand and do not incorporate WiFi-side channel quality measurements, such as RSSI or channel congestion. The system was validated only in an RF-simulated environment and has not tested under real wireless channel conditions, where the signal quality and congestion vary dynamically. The present work addresses this gap by designing a system architecture that continuously monitors channel quality on both 5G and WiFi and triggers RAT switching based on the observed signal and congestion conditions, independent of traffic demand.

III. Proposed Bidirectional Traffic Steering System

This section presents the proposed multi-RAT bidirectional traffic steering system in detail. We first provide the overview of system-level architecture and its components, and then describe the role and operation of each component.

A. System Overview

The overall system architecture is presented in Fig. 1. As shown in the figure, the proposed system is organized into four layers: the Non-RT RIC layer, Near-RT RIC layer, control plane layer, and data plane layer. Firstly, the Non-RT RIC layer consists of the Non-RT RIC and the A1 Mediator, and communicates with the Near-RT RIC layer over the A1 interface. Secondly, the Near-RT RIC layer consists of Near-RT RIC and the xApp, and interacts with the control plane via the E2 interface. Thirdly, the control plane consists of the O-gNB, E2 Adapter, CN Agent, and UE Agent. Finally, the data plane comprises the 5G and WiFi paths, both of which are controlled under the same Near-RT RIC.

B. Non-RT RIC and Near-RT RIC Layer

The Non-RT RIC operates on a longer timescale and is responsible for defining high-level steering policies. It employs an rApp that monitors the network-level trends and generates steering parameters. These parameters are packaged into an A1-P policy and forwarded to the Near-RT RIC over the A1 interface via the A1 Mediator. This design allows the operator to modify steering behavior by updating the policy without modifying the xApp. The Near-RT RIC forwards the policy to the xApp, which plays a role as the steering decision engine.

At each measurement reporting interval, the xApp collects measurements from both E2 Nodes. Specifically, it receives 5G-side measurements including RSRP, SINR, MCS index, and PRB utilization by using KPM indication messages from the O-gNB, and WiFi-side measurements including RSSI and retry rate (i.e. the number of retransmissions divided by the total number of transmission attempts) by using WiFi Measurement and Control (WMC) indication messages from the E2 Adapter. Actually, WMC is a customized E2SM extending the E2 interface to cover non-3GPP access because no standardized O-RAN service model for WiFi integration is currently available. Because the O-gNB and E2 Adapter may send measurements asynchronously, the xApp always uses the most recently received value from each side. Based on the collected measurements, the xApp compares each metric against the corresponding policy parameters and determines whether to steer the UE to WiFi (*steerToWifi*) or 5G (*steerTo5G*). The steering decision is then encapsulated in an RC Control message, which is sent to both the O-gNB and E2 Adapter and triggers enforcement across both domains.

C. Control and Data Plane

As mentioned earlier, the control plane consists of the O-gNB, E2 Adapter, CN Agent, and UE Agent. Each component is responsible for a specific part of the steering enforcement process, and together they translate the steering decisions issued by the xApp into actual path changes in the data plane.

The O-gNB communicates with the xApp via the E2 interface. It uses ASN.1 PER for message encoding and SCTP for reliable and efficient message delivery. The O-gNB operates as an E2 Node on the 5G domain and registers two RAN Functions to the Near-RT RIC when the corresponding connection is established. The first RAN Function is based on the KPM E2SM and enables the xApp to subscribe to periodic KPM indication messages from the O-gNB. The second RAN Function is based on the RC E2SM and allows the xApp to dispatch steering decisions to the O-gNB using RC Control messages.

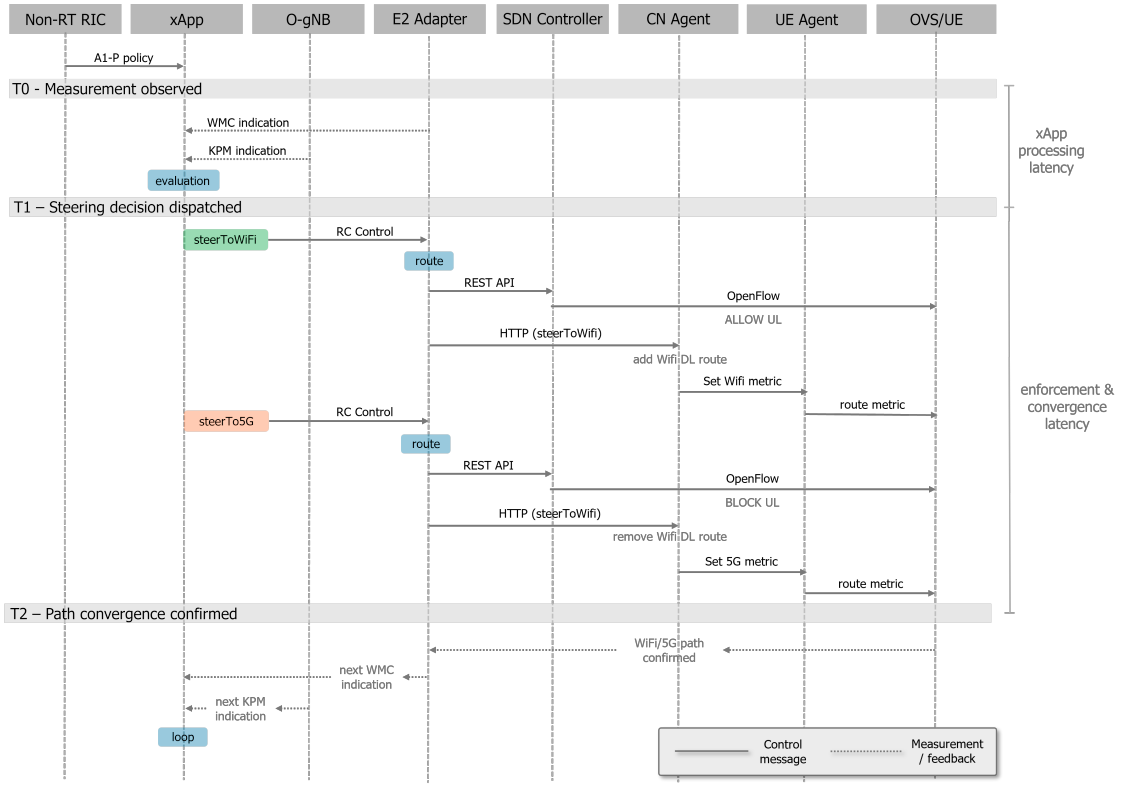


Fig. 2. Control loop procedure for multi-RAT bidirectional traffic steering.

The E2 Adapter serves as a bridge between the Near-RT RIC and the WiFi domain and registers itself as an E2 Node to the Near-RT RIC. On the measurement side, it collects the RSSI and retry rate values from the WiFi AP at each reporting interval and forwards them to the xApp using WMC indication messages. On the control side, when the E2 Adapter receives an updated steering decision from the xApp, it translates the decision into enforcement actions and then forwards uplink enforcement to the SDN controller and downlink enforcement to the CN Agent, respectively. As shown in Fig. 1, the E2 Adapter is composed of three internal modules that support both measurement reporting and steering enforcement. The E2 Termination module manages the SCTP connection to the Near-RT RIC and handles message encoding and decoding using the ASN.1 PER. It also registers a RAN Function based on the WMC E2SM to the Near-RT RIC when the connection is established. This RAN Function enables the xApp to receive WiFi measurements using WMC indication messages and to send steering commands using RC Control messages. The Measurement Collector module polls the WiFi AP over the ONOS REST API at each reporting interval, retrieves per-station RSSI and retry rate, and constructs a WMC indication message that is forwarded to the xApp. The Steering Action Translator module receives RC Control messages from the xApp and translates the encoded steering action into enforcement calls, which are forwarded to the SDN controller for uplink path switching and to the CN Agent for downlink path switching. This modular design confines all WiFi-specific logic within the E2 Adapter, allowing the xApp and Near-RT RIC to interact with the WiFi domain over standard E2 interfaces, as they do with any other E2 Node.

The SDN controller manages the uplink path at the network level by installing or removing flow rules on the OVS switch. These flow rules determine which uplink traffic from the UE is permitted to pass through the OVS switch. By updating these rules in response to steering decisions received from the E2 Adapter, the SDN controller enforces uplink path switching without requiring any configuration changes on the UE itself.

The CN Agent and UE Agent are introduced to perform path steering on the network side and the UE side, respectively. The CN Agent controls the downlink path on the network side, i.e. it adds a routing rule that forwards the downlink traffic to the UE through the WiFi path when a *steerToWifi* decision is received. Conversly, it removes the routing rule so that downlink traffic is delivered over the 5G network when a *steerTo5G* decision is received. The CN Agent also notifies the UE Agent to update the uplink routing configuration on the UE side. The UE Agent is executed on the UE and adjusts the routing metric of each network interface based on instructions from the CN Agent, thereby ensuring that the UE transmits traffic over the designated interface. This enforces uplink path switching consistently at both the network and device levels. The UE Agent also maintains a static route to the CN Agent, ensuring that the control communication between the CN Agent and UE Agent is preserved regardless of changes in the default routing configuration during path switching.

The data plane comprises two forwarding paths that operate in parallel under the Near-RT RIC. The 5G path carries traffic from the source to the UE through the UPF and O-gNB while the WiFi path carries traffic from the source to the UE through the OVS switch and WiFi AP. For each steering decision, both uplink and downlink are switched together to ensure that traffic flows over the designated access technology.

IV. Policy-Aware Steering Design

In this section, we describe how the proposed system makes and enforces steering decisions. We first present the steering policy delivered from the Non-RT RIC to the xApp, and then explain the steering decision logic implemented within the xApp, finally describe the closed-loop control procedure that enforces steering decisions in the data plane.

A. Steering Policy and Decision Logic

The steering behavior of the xApp is governed by an A1-P policy delivered from the Non-RT RIC through the A1 Mediator. Each policy defines four parameters. The upper RSSI threshold θ_{upper} and lower RSSI threshold θ_{lower} establish the boundaries for WiFi RSSI-based steering decisions. The retry rate threshold θ_{retry} indicates the degree of channel congestion on the WiFi side that triggers a RAT switch. In addition to these threshold parameters, each policy also carries a time-to-live (TTL), which determines how long the policy remains valid. If the policy is not refreshed before the TTL expires, the xApp suspends steering and maintains the current RAT until a new valid policy is received.

At each measurement reporting interval, the xApp compares the collected measurements with the policy parameters and determines the appropriate steering action. The decision logic differs depending on which RAT is currently active on the UE. When the UE is on 5G, a *steerToWifi* decision is issued if the following equation is satisfied:

$$\text{RSSI} > \theta_{upper} \text{ and RetryRate} < \theta_{retry}. \quad (1)$$

Equation (1) holds when both the RSSI and retry rates must simultaneously satisfy their respective thresholds. This ensures that the proposed system steers toward WiFi only when the WiFi link is stable in terms of signal strength and network channel congestion. When the UE is on WiFi, a *steerTo5G* decision is issued if the following equation is satisfied:

$$\text{RSSI} < \theta_{lower} \text{ or RetryRate} \geq \theta_{retry}. \quad (2)$$

Equation (2) holds when the RSSI falls below the lower threshold, indicating signal degradation, or when the retry rate exceeds its threshold, indicating network channel congestion. Either metric alone is sufficient to trigger a return to 5G, because a WiFi link may experience congestion even when the signal strength remains high. When neither condition is satisfied, the xApp maintains the current RAT and does not issue a steering decision. This occurs within the hysteresis band, as defined by the following equation:

$$\theta_{lower} \leq \text{RSSI} \leq \theta_{upper} \text{ and RetryRate} < \theta_{retry}. \quad (3)$$

Equation (3) defines the hysteresis band in which neither *steerToWifi* nor *steerTo5G* is triggered. This mechanism prevents repeated switching when the RSSI fluctuates around a boundary value and ensures stable steering behavior under varying channel conditions.

B. Control Loop Procedure

Once a steering decision is made, it must be enforced within the latency bounds imposed by the O-RAN Near-RT RIC. To characterize the end-to-end responsiveness of the control loop, three timestamps are defined along the message flow, as illustrated in Fig. 2. T0 is the first timestamp and marks the moment at which the xApp receives measurement indication messages from both E2 Nodes. At this point, the xApp updates its per-UE state and evaluates the active steering policy against the received measurements. T1 is the second timestamp and marks the moment at which the xApp dispatches the steering decision as an RC Control message to the E2 Node. T2 is the third timestamp and marks the moment at which the first packet traversing the new path is confirmed. This confirmation is reported back to the E2 Nodes, which then issue the next indication message, thereby advancing the control loop back to T0 and completing one full cycle.

As shown in Fig. 2, two latency intervals are measured along the control loop. The T0 to T1 interval captures the xApp processing latency, i.e., the time required to evaluate the steering policy and issue a decision. The T1 to T2 interval captures enforcement and convergence latency, i.e., the time from when the steering decision is dispatched to when the data plane has fully switched to the new path. The sum of these two intervals, i.e., T0 to T2, represents the end-to-end control loop latency of the proposed system. The enforcement actions executed between T1 and T2 are determined by the outcome of the steering decision. On a *steerToWifi* decision, the E2 Adapter instructs the SDN controller to install an ALLOW UL rule on the OVS switch, and instructs the CN Agent to add a downlink route toward the WiFi path. The CN Agent subsequently instructs the UE Agent to set the WiFi interface as the preferred uplink path. On a *steerTo5G* decision, the E2 Adapter instructs the SDN controller to install a BLOCK UL rule on the OVS switch and instructs the CN Agent to remove the WiFi downlink route. The CN Agent then instructs the UE Agent to set the 5G interface as the preferred uplink path.

V. Experimental Evaluation

In this section, we present the experimental results of the proposed system on a real testbed. We first describe the testbed configuration and experimental conditions, then examine the control loop latency to verify that the closed-loop operation satisfies the O-RAN Near-RT RIC requirement, and finally evaluate the steering behavior under both the RSSI-based and retry rate-based triggers.

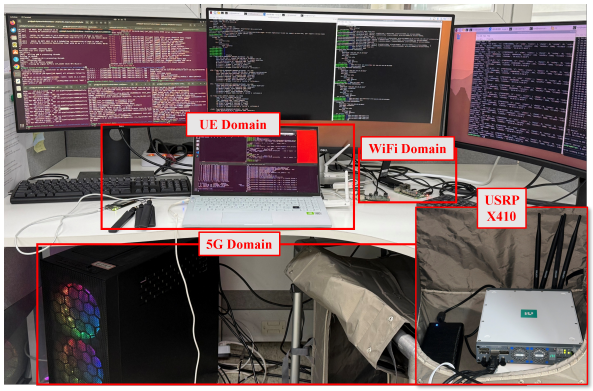


Fig. 3. Construction of a real testbed for the proposed system.

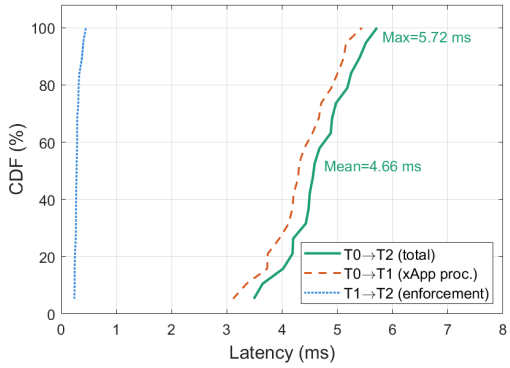


Fig. 4. CDF of control loop latency intervals.

TABLE I
TESTBED CONFIGURATION

Domain	Component	Details
5G	gNB	OAI 5G SA, Band n78, USRP X410
	5G core	OAI CN5G Fed
	Near-RT RIC	FlexRIC
WiFi	AP	Raspberry Pi 4, hostapd, 802.11ac, 5 GHz
	OVS Switch	Raspberry Pi 4, OpenvSwitch
	SDN Controller	ONOS 2.7.0
UE	5G interface	Quectel RM500Q-GL
	WiFi interface	USB WiFi adapter, 802.11ac

A. Experimental Setup

The proposed system is fully implemented and tested on a real testbed. The testbed is constructed using a server host, an Ettus USRP X410, a pair of Raspberry Pi devices, and a laptop UE. Fig. 3 shows the resulting testbed including the 5G domain, the WiFi domain, and the UE domain. The server host runs Ubuntu 22.04 LTS on an Intel Core i9-12900K processor with 128 GB of RAM, and is connected to the USRP X410, which is placed inside an EMI shielding tent. Table I summarizes the detailed components of each domain. The 5G domain comprises the USRP X410 as the radio front-end and an OAI 5G SA gNB operating on a single n78 cell. The 5G core is deployed using the OAI CN5G Fed [19], and the Near-RT RIC is instantiated on FlexRIC. The WiFi domain comprises a Raspberry Pi 4 running hostapd as the WiFi AP, operating at 5 GHz under 802.11ac, and a second Raspberry Pi 4 running OpenvSwitch [20] as the OVS switch. ONOS (version 2.7.0) is deployed as the SDN controller to manage the OVS switch and install the OpenFlow rules for uplink path control. The UE is a laptop equipped with a Quectel RM500Q-GL module [21] for the 5G interface and a MediaTek MT7610U USB WiFi adapter [22] for the WiFi interface, supporting 802.11ac. To evaluate the DL throughput performance, traffic is generated using iperf3 at a target rate of 10 Mbps, and the throughput is measured at the UE by monitoring per-interface byte counters every second.

All experiments are conducted under a common A1-P policy that set θ_{upper} to -65 dBm, θ_{lower} to -72 dBm, and θ_{retry} to 0.5, respectively. The control loop latency is measured across 19 steering events using the timestamps defined in Section IV-C. Steering behavior is then investigated under two types of WiFi channel degradation: RSSI-based signal degradation and retry rate-based channel congestion. To trigger a RSSI-based steering event, the UE is moved away from the AP until the RSSI falls below θ_{lower}. To trigger a retry rate-based steering event, additional WiFi load is introduced to increase the retry rate above θ_{retry}. For each steering trigger, a single steering event is first examined to verify the correct detection and path transition. An extended session then demonstrates sustained bidirectional operations over time. In both cases, throughput is compared with the single-RAT baseline to assess the effectiveness of the closed-loop steering mechanism.

B. Control Loop Latency

To show that the proposed system satisfies the O-RAN Near-RT RIC latency requirement, the T0, T1, and T2 timestamps are used to measure the control loop latency. Fig. 4 shows the CDF of the T0 to T1, T1 to T2, and T0 to T2 latency intervals. The interval between T0 and T1 has a mean of 4.37 ms and a maximum of 5.45 ms, which is over 93% of the total end-to-end latency. It is clearly observed that most of the control loop delay is attributed to xApp processing. By contrast, the interval between T1 and T2 has a mean of 0.30 ms and a maximum of 0.45 ms, tightly concentrated below 0.5 ms across all events. Hence the steering enforcement introduces consistent and negligible overhead compared to xApp processing. Consequently, the end-to-end time latency between T0 and T2 has a mean of 4.66 ms and a maximum of 5.72 ms, both of which satisfy the O-RAN Near-RT RIC control loop requirement of 10 ms. These experimental results show that the E2 Adapter successfully integrates the WiFi domain into the O-RAN Near-RT RIC control loop with minimal overhead. It obviously demonstrates that non-3GPP access can be incorporated into the O-RAN RIC framework without compromising the real-time control capability of the Near-RT RIC.

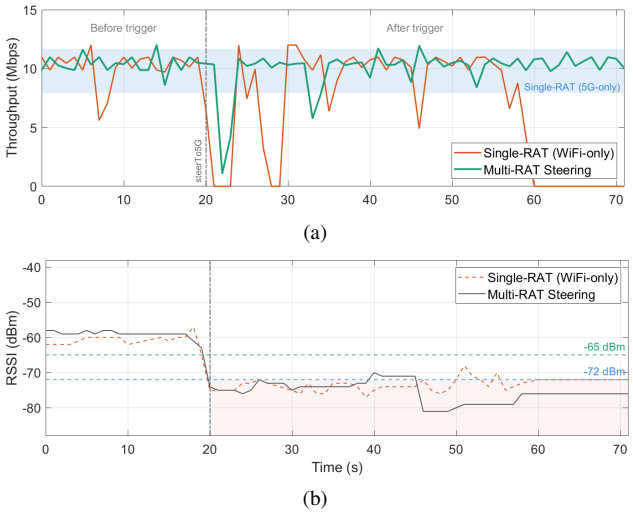


Fig. 5. (a) DL throughput and (b) WiFi RSSI around an RSSI-based steerTo5G event under multi-RAT steering and single-RAT baseline.

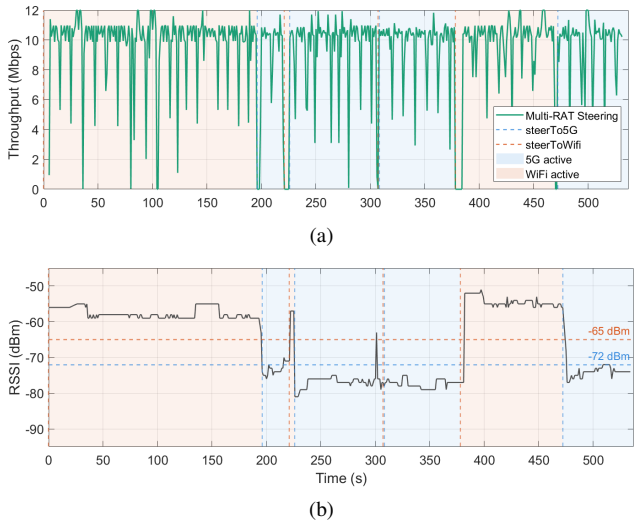


Fig. 6. (a) DL throughput and (b) WiFi RSSI over an extended session under RSSI-based multi-RAT bidirectional steering.

C. Steering Performance

This section presents that the proposed system correctly monitors WiFi channel and network conditions in real time, and maintains throughput continuity by bidirectional traffic steering between 5G and WiFi. Basically, two types of steering are examined. That is, RSSI-based steering is triggered by WiFi signal degradation, and retry rate-based steering is activated by WiFi network congestion. Two scenarios are tested for both RSSI-based steering and retry rate-based steering, i.e. a single steering event to check whether the proposed system detects the WiFi channel and network conditions correctly and performs the suitable path transition, and a sequence of steering events to demonstrate that the proposed system sustains bidirectional operations under dynamically varying wireless network conditions.

RSSI-Based Steering: This experiment investigates the steering behavior under WiFi signal degradation. First of all, the UE is connected over the WiFi path and moved away from the AP until the RSSI falls below θ_{lower}. Fig. 5 then presents the resulting DL throughput and WiFi RSSI with the single-RAT baseline included for comparison. Before the *steerTo5G* decision occurs at t = 20 s, the UE remains on the WiFi path with throughput at approximately 10 Mbps and RSSI at approximately -60 dBm, above θ_{lower}. As the UE moves farther from the AP, the RSSI in Fig. 5(b) drops to -74 dBm, falling below the θ_{lower}. The xApp subsequently detects the threshold crossing and issues a *steerTo5G* decision. As shown in Fig. 5(a), throughput under multi-RAT steering is then maintained at approximately 9.4 Mbps after the transition, matching the 5G single-RAT baseline range of 8 to 11 Mbps. In contrast, under the WiFi single-RAT baseline, throughput drops toward zero under the same RSSI degradation and does not recover. These results confirm that the proposed system maintains throughput continuity by promptly switching to 5G and that the throughput achieved after the transition aligns with the 5G single-RAT baseline. Conversely, the WiFi single-RAT baseline fails to sustain the connection once the RSSI falls below θ_{lower}.

To check whether the proposed system executes RSSI-based bidirectional steering consistently when a sequence of steering events occurs, an extended session of approximately 530 s is conducted in which the UE is repeatedly moved toward and away from the AP. Fig. 6 shows the DL throughput and WiFi RSSI during this session. The RSSI in Fig. 6(b) crosses both θ_{upper} and θ_{lower} several times during the session. On each threshold crossing, the xApp issues the corresponding steering decision and switches the active RAT accordingly. As shown in Fig. 6(a), throughput is maintained at approximately 10 Mbps regardless of which RAT is active. During WiFi active periods, mean throughput is 9.79 Mbps, whereas during 5G active periods it is 9.58 Mbps. This demonstrates that the proposed system successfully exploits both access technologies without sacrificing throughput continuity. Short throughput drops are observed at each transition point as the data plane switches to the new path; however, throughput recovers promptly after every transition. The extended session shows that the proposed system continuously adapts RAT selection to fluctuations in the WiFi RSSI and sustains stable throughput across multiple bidirectional steering transitions.

Retry rate-Based Steering: This experiment examines steering behavior under WiFi network congestion, independent of the signal strength. While the RSSI remains above θ_{upper}, additional traffic is inserted to make the retry rate caused by congestion larger than θ_{retry}. Fig. 7 shows the DL throughput and WiFi retry rate with the single-RAT baseline for comparison. Before the *steerTo5G* decision occurs at t = 20 s, both multi-RAT steering and the WiFi single-RAT baseline exhibit comparable throughput at approximately 10 to 11 Mbps in Fig. 7(a), with a retry rate below 0.05 in Fig. 7(b). As the WiFi load increases, the retry rate rises to 0.57, exceeding θ_{retry}, while the RSSI remains at approximately -56 dBm. The xApp detects this threshold crossing and issues a *steerTo5G* decision.

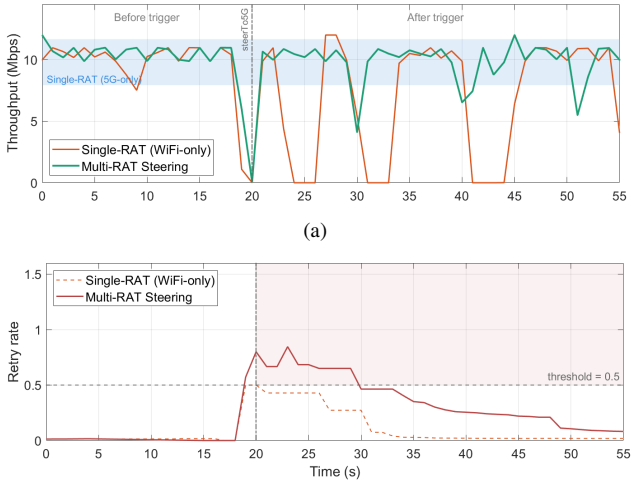


Fig. 7. (a) DL throughput and (b) WiFi retry rate around a retry rate-based steerTo5G event under multi-RAT steering and single-RAT baseline.

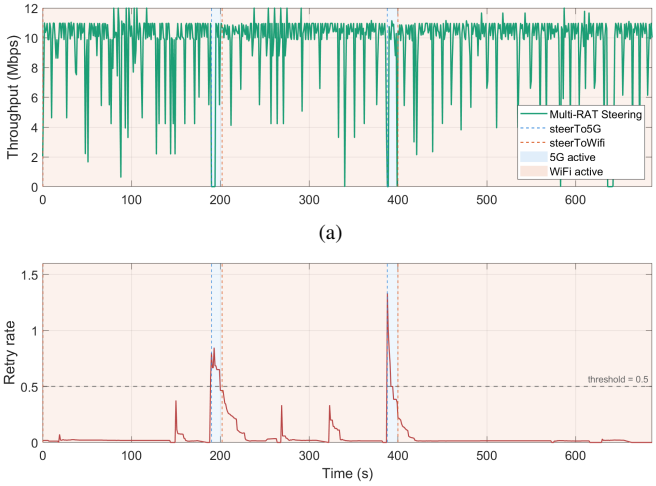


Fig. 8. (a) DL throughput and (b) WiFi retry rate over an extended session under retry rate-based multi-RAT bidirectional steering.

As shown in Fig. 7(a), throughput under multi-RAT steering recovers to approximately 10 Mbps, consistent with the 5G single-RAT baseline. By contrast, under the WiFi single-RAT baseline, throughput remains unstable because the high retry rate causes repeated retransmissions on the WiFi link. These results confirm that the proposed system restores throughput by switching to 5G immediately the retry rate exceeds θ_{retry}, even when RSSI alone does not indicate channel degradation.

To investigate whether the proposed system performs retry rate-based bidirectional steering properly when a sequence of steering events happens, an extended session of approximately 700 s is conducted in which channel congestion is repeatedly introduced and removed. Fig. 8 shows the DL throughput and WiFi retry rate during this session. The retry rate in Fig. 8(b) crosses θ_{retry} twice during the session, each time triggering the corresponding steering decision and switching the active RAT between WiFi and 5G. As shown in Fig. 8(a), throughput remains close to 10 Mbps across the entire session, with mean throughput of 9.49 Mbps during WiFi active periods and 9.66 Mbps during 5G active periods. The extended session demonstrates that the proposed system responds to retry rate fluctuations by steering the UE to 5G during congestion and back to WiFi once the channel recovers. Throughput remains consistent across all steering transitions.

VI. Conclusion

In this work, we have presented an O-RAN RIC-based system for bidirectional traffic steering between 5G and WiFi. The E2 Adapter registers the WiFi domain as an E2 Node to the Near-RT RIC. The xApp collects WiFi-side measurements and enforces steering decisions through standard E2 interfaces. The xApp continuously monitors the channel quality of both access technologies and switches the UE between 5G and WiFi based on real-time RSSI and retry rate measurements. The proposed system is validated on a real testbed with actual RF transmission. The end-to-end control loop latency achieve a mean of 4.66 ms, satisfying the O-RAN Near-RT RIC requirement of 10 ms. Experimental results further confirm that the proposed system correctly detects both RSSI degradation and channel congestion as independent steering triggers and responds with the appropriate steering decision in each case. The proposed system also sustains autonomous bidirectional operations over time, demonstrating that closed-loop steering based on real-time channel quality is both feasible and effective in dynamic channel environments.

Future work will explore adaptive policy update mechanisms and data-driven steering policies, including a DQN-based decision module. In addition, the customized WMC E2SM defined in this work will be considered as a candidate contributor to the O-RAN standardization process.

Acknowledgment

This work was partly supported by Institute of Information & communications Technology Planning & Evaluation (IITP) grant funded by the Korea government(MSIT) (No. RS-2026-25527078) and National Research Foundation of Korea (NRF) grant funded by the Korea government(MSIT) (No. RS-2026-25486402).

References

[1] L. Bisti, L. Lenzini, E. Mingozzi, and C. Vallati, "Efficient handoff for mass transit connectivity using IEEE 802.11," *arXiv:1508.00131*, 2015.

[2] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, 2000.

[3] *O-RAN Architecture Description*, V.17.0, O-RAN.WG1.TS.OAD-R005-v17.00, O-RAN ALLIANCE WG1, O-RAN ALLIANCE e.V., Alfter, Germany, 2026.

[4] *O-RAN Near-Real-Time RIC Architecture*, V.8.0, O-RAN.WG3.TS.RICARCH-R005-v08.00, O-RAN ALLIANCE WG3, O-RAN ALLIANCE e.V., Alfter, Germany, 2026.

[5] *Non-Real-Time RAN Intelligent Controller Architecture*, V.7.0, O-RAN.WG2.TS.Non-RT-RIC-ARCH-R004-v07.00, O-RAN ALLIANCE WG2, O-RAN ALLIANCE e.V., Alfter, Germany, 2025.

[6] O. Kwon, Y. Go, Y. Park, and H. Song, "MPMTP: MultiPath Multimedia Transport Protocol Using Systematic Raptor Codes Over Wireless Networks," *IEEE Transactions on Mobile Computing*, vol. 14, no. 9, pp. 1903–1916, Sep. 2015.

[7] D. Ho, G. Park, and H. Song, "Game-Theoretic Scalable Offloading for Video Streaming Services Over WiFi and LTE Networks," *IEEE Transactions on Mobile Computing*, vol. 17, no. 5, pp. 1090–1104, May 2018.

[8] Y. Go, H. Noh, G. Park, and H. Song, "Energy-Efficient HTTP Adaptive Streaming With Hybrid TCP/UDP Over Heterogeneous Wireless Networks," in *Proceedings of the 20th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Washington, DC, USA, 2019.

[9] F. Kaltenberger, A. P. Silva, A. Gosain, L. Wang, and T.-T. Nguyen, "OpenAirInterface: Democratizing innovation in the 5G Era," *Computer Networks*, vol. 176, p. 107284, 2020.

[10] R. Schmidt, M. Irazabal, and N. Nikaein, "FlexRIC: an SDK for next-generation SD-RANs," in *Proceedings of the 17th International Conference on Emerging Networking Experiments and Technologies (CoNEXT '21)*, New York, NY, USA, 2021, pp. 411–425.

[11] P. Berde, M. Gerola, J. Hart, Y. Higuchi, M. Kobayashi, T. Koide, *et al.*, "ONOS: towards an open, distributed SDN OS," in *Proceedings of the Third Workshop on Hot Topics in Software Defined Networking (HotSDN '14)*, New York, NY, USA, 2014, pp. 1–6.

[12] O-RAN ALLIANCE. Accessed: Jun. 21, 2026. [Online]. Available: https://www.o-ran.org/.

[13] *O-RAN E2 Service Model (E2SM)*, V.7.0, O-RAN.WG3.TS.E2SM-R004-v07.00, O-RAN ALLIANCE WG3, O-RAN ALLIANCE e.V., Alfter, Germany, 2025.

[14] *System architecture for the 5G system (5GS)*, Technical Specification (TS) 23.501, 3rd Generation Partnership Project (3GPP), version 16.11.0, 2021.

[15] M. A. Habib, H. Zhou, P. E. Iturria-Rivera, M. Elsayed, M. Bavand, R. Gaigalas, *et al.*, "Traffic Steering for 5G Multi-RAT Deployments using Deep Reinforcement Learning," in *Proceedings of the 20th Consumer Communications and Networking Conference (CCNC '23)*, Las Vegas, NV, USA, 2023, pp. 164–169.

[16] M. A. Habib, H. Zhou, P. E. Iturria-Rivera, M. Elsayed, M. Bavand, R. Gaigalas, *et al.*, "Hierarchical Reinforcement Learning Based Traffic Steering in Multi-RAT 5G Deployments," in *Proceedings of the International Conference on Communications (ICC '23)*, Rome, Italy, 2023, pp. 100–105.

[17] P. K. Mangipudi, S. Boamah, L. Carvajal, and J. McNair, "COHERE: Congestion-aware Offloading and Handover via Empirical RAT Evaluation for Multi-RAT Networks," *arXiv:2511.00439*, 2025.

[18] D. Kefalas, N. Makris, T. Korakis, and S. Fdida, "Traffic Steering for O-RAN Multi-RAT 5G Networks Using ML-Based Demand Forecasting," in *Proceedings of Conference on Network Function Virtualization and Software-Defined Networking (NFV-SDN '25)*, 2025.

[19] OpenAirInterface. Accessed: Jun. 21, 2026. [Online]. Available: https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-fed.

[20] B. Pfaff, J. Pettit, T. Koponen, E. J. Jackson, A. Zhou, J. Rajahalme, *et al.*, "The Design and Implementation of Open vSwitch," in *Proceedings of the 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI '15)*, Oakland, CA, USA, 2015, pp. 117–130.

[21] Quectel Wireless Solutions. Accessed: Jun. 21, 2026. [Online]. Available: https://www.quectel.com.

[22] MediaTek Inc. Accessed: Jun. 21, 2026. [Online]. Available: https://www.mediatek.com/products/broadband-wifi/mt7610u.