

Toward Handover-Free Mobility Management in FD-RAN: Architecture, Challenges, and Solutions

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ABSTRACT

The forthcoming sixth-generation (6G) mobile networks are envisioned to provide seamless high rate services under the scenario of high user mobility, which cannot be adequately supported by existing mobility management frameworks in the fifth-generation (5G) mobile networks. In this article, to deal with these issues, we investigate mobility management problem in a novel fully-decoupled radio access network (FD-RAN) architecture designed for 6G. Specifically, we first give an in-depth elaboration on the architecture and mechanisms of FD-RAN, explore potential mobility management challenges, and then propose a handover-free mobility management framework tailored for FD-RAN, aiming at providing continuous, satisfactory, and on-demand services for mobile users. Finally, we present a case study where an artificial intelligence (AI)-empowered approach is applied for mobility management in the downlink FD-RAN, and we validate its effectiveness through extensive simulations.

INTRODUCTION

Throughout the evolution of mobile networks, mobility management has always been one of the challenging tasks. In the current era of fifth-generation (5G) mobile networks, to maintain service continuity for mobile user equipment (UE), handover mechanism is employed, which means changing the UE's connection from the serving base station (BS) to a neighbor BS. Currently, the handover process in 5G requires UE to first disconnect from the source BS before establishing connection with the target BS. This inevitably results in a short interruption of communication, hence this kind of handover is called hard handover. How to make the hard handover softer, that is, reducing handover interruption time, has long been an area of research interest. Recently, some mobility enhancements about soft handover for 5G have been proposed, such as dual active protocol stack (DAPS) handover in 3GPP Release 16 standards [1]. In DAPS handover, UE remains connection with the source BS until it is able to transceive data with the target BS, thereby the handover interruption time is reduced.

However, DAPS has not been formally adopted in commercial 5G due to constraints related to technical complexity, device compatibility, and late standards.

With the maturation and commercialization of 5G, inherent limitations of this system have become increasingly apparent [2]. Due to higher frequency bands, smaller BS coverage and denser BS deployment, 5G mobile UEs suffer from more frequent handovers and consequent service interruption [3]. Moreover, the inflexible BS association mode and fixed resource scheduling method of 5G networks make it difficult to meet the diverse and dynamic quality of service (QoS) requirements of UEs. Meanwhile, sixth-generation (6G) mobile networks are envisaged to evolve remarkably from 5G and provide mobility enhancement supports. How to provide continuous and on-demand services in 6G under the scenario of high UE mobility remains a significant challenge.

From the first generation to 6G, achieving green, flexible and lightweight communication has been a continuous pursuit in the design of mobile network architecture [4]. A recently proposed original radio access network (RAN) architecture, known as the fully-decoupled RAN (FD-RAN) [5], is recognized as a key development trend in future 6G [4], and has garnered significant attention from both academia and industry. In FD-RAN, traditional BSs are logically and physically decoupled into control BS (CBS) and data BSs, while data BSs are further decoupled into independently deployed uplink BSs (UBSs) and downlink BSs (DBSs). Moreover, multi-connectivity has become the default UE-BS association mode in FD-RAN where multiple UBSs and DBSs collaborate to serve every UE. The complete decoupling and dynamic multi-connectivity features of FD-RAN facilitate elastic UE-BS association and resource cooperation. In 6G era, FD-RAN is expected to enhance networking flexibility and improve resource utilization efficiency [6], [7], [8], aiming at providing satisfactory and adaptable services for mobile UEs.

However, FD-RAN brings forth new challenges for traditional mobility management framework. Specifically, due to the complete decoupling of BSs, UE will experience different types of handovers with different types of BSs, meaning that

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Note that in the handover-free FD-RAN mobility management, each UE is cooperatively served by a cluster of BSs called BCS. As the UE moves, it will not experience traditional hard handovers between single source BS and target BS. Instead, each UE is consistently served by its own BCS, and the BS members within the BCS will dynamically change to follow the UEs movement.

handover signaling procedures need redesign. Moreover, in multi-connectivity mode, each UE is served by a cluster of BSs which we refer to as the BSs cooperation set (BCS), both in uplink and downlink. Therefore, mobility management in FD-RAN no longer involves handovers between individual BSs, but rather updating UE's BCS which includes replacing, adding, or removing serving BSs from the BCS. In addition, since FD-RAN aims at providing personalized on-demand service for each UE, mobility management in FD-RAN should have the capability to change UE's serving BSs not only based on its movement, but also in response to its service demands. Thus, typical event-based handover policy [9] designed for single-connectivity in 5G is inapplicable. So it will be of great significance to develop a novel mobility management framework specialized for FD-RAN.

In this article, we propose a handover-free mobility management framework tailored for complete BS decoupling and multi-connectivity characteristics of FD-RAN, which supports seamless connection and dynamic services for mobile UEs. Note that in the handover-free FD-RAN mobility management, each UE is cooperatively served by a cluster of BSs called BCS. As the UE moves, it will not experience traditional hard handovers between single source BS and target BS. Instead, each UE is consistently served by its own BCS, and the BS members within the BCS will dynamically change to follow the UEs movement. So in handover-free mobility management, for each mobile UE, the traditional handover concept is replaced by BCS updating. The proposed framework in this article is partially based on the ideas proposed in [11]. The difference is that the paper [11] only proposed an algorithm for BCS updating in downlink FD-RAN. However, this article introduces the network architecture and mechanism of FD-RAN in detail, designs the protocol and procedures of handover-free mobility management, and proposes a two-layer mobility management decision algorithm including both BCS updating and transmission power control. The major contributions of this article are summarized as follows:

- We give an in-depth elaboration on the architecture and mechanisms of FD-RAN including network components, protocol stack, and multi-connectivity transmission modes, then we present some mobility management key points in FD-RAN.
- We propose a handover-free FD-RAN mobility management framework named HFMM in response to the challenges posed by FD-RAN characteristics and the vision of 6G. We specify main protocols and procedures in HFMM framework. Specifically, procedures such as user initial access, BCS initiating, and BCS updating are illustrated in detail.

- To deal with the downlink HFMM decisions, we design a two-layer hierarchical deep reinforcement learning (HDRL) algorithm for downlink BCS updating and transmission power control, respectively. Simulation results verify that the HDRL algorithm could provide more continuous services and achieve higher QoS satisfaction rate in downlink FD-RAN scenario compared to benchmarks and other comparing algorithms, while requiring fewer BCS updates and network resource usage.

The remainder of this article is organized as follows. We first introduce the architecture and mechanism of FD-RAN. Next, details of the proposed HFMM framework are illustrated. Then, an AI-empowered mobility management approach for downlink FD-RAN is presented and evaluated. Finally, we provide some concluding remarks.

ARCHITECTURE AND MECHANISM OVERVIEW OF FD-RAN

In this section, we provide a detailed description of FD-RAN's network composition, multi-connectivity cooperation mechanisms, and protocol stack. Then, we summarize the design ideas of FD-RAN and discuss some mobility management key points arising from its characteristics and mechanisms.

THE COMPONENTS OF FD-RAN

Figure 1 illustrates an overall network view of FD-RAN that includes components such as UEs, UBSs, DBSs, a CBS, and an edge cloud (EC).

1) UE: UEs are single-antenna, supposed to be capable of simultaneously connecting to multiple BSs on multiple frequency bands. UEs can have various services with different serving rate demands.

2) UBS: UBSs are multi-antenna micro BSs dedicated to supporting simplex uplink data plane, which have only low physical (PHY) layer processing capabilities.

3) DBS: DBSs are multi-antenna small BSs dedicated to supporting simplex downlink data plane, which have only PHY processing capabilities.

4) CBS: CBS is a macro BS operating in low-frequency band with wide coverage, supporting duplex control plane. CBS has only PHY processing capabilities, bears the control channel and transfers control signaling between UEs and EC.

5) EC: EC centralizes most of processing capabilities in the network since FD-RAN is essentially a cloud RAN (C-RAN) architecture [10]. All UBSs, DBSs, and the CBS are connected to the EC via fiber optics. The EC consists of a central data unit (CDU) and a central control unit (CCU). Specifically, the CCU serves as anchor point for control plane, bears functions such as admission control and mobility management. The CDU serves as anchor point for data plane, bears functions such as baseband processing and data stream splitting.

MULTI-CONNECTIVITY TRANSMISSION MODES

In FD-RAN, regardless of uplink or downlink, each UE is served by clusters of BSs. The UBS cluster is called uplink BCS (UBCS), and the DBS cluster is called downlink BCS (DBCS). So how

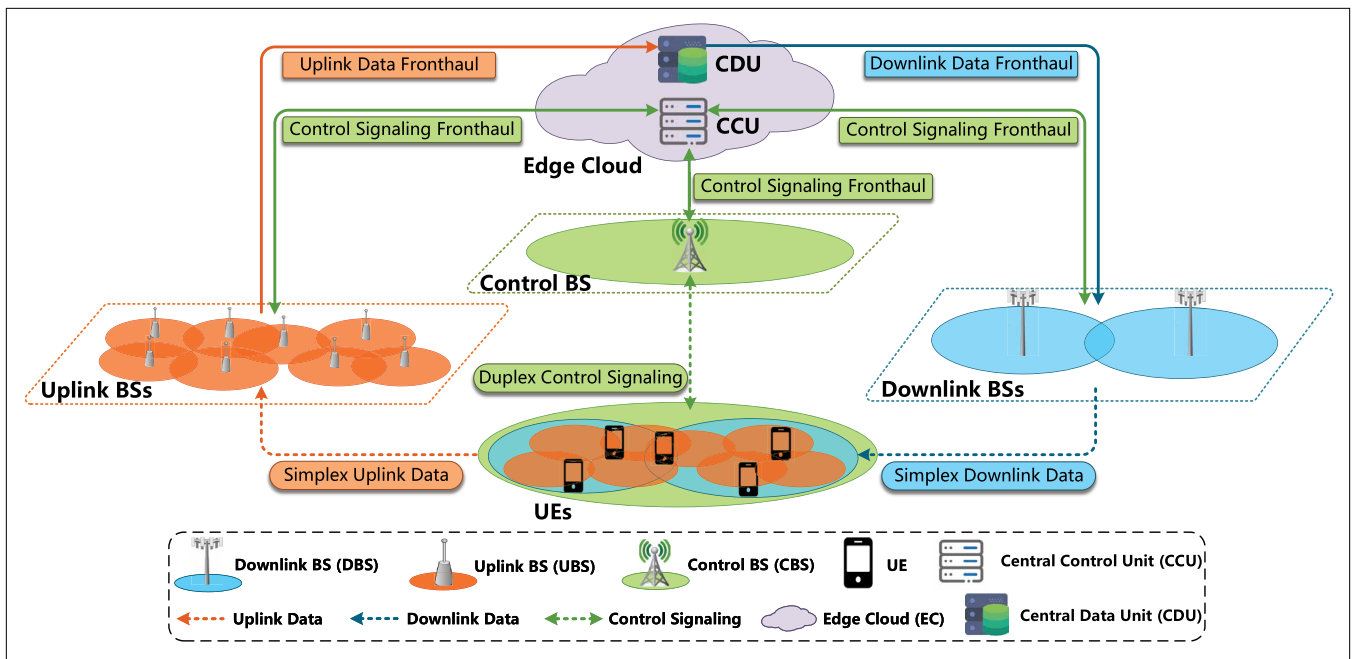


FIGURE 1. A network view of FD-RAN includes UE, uplink BS, downlink BS, control BS, and edge cloud.

do multiple BSs within UBCS and DBCS serve a UE cooperatively? Here we provide a brief overview of the multi-connectivity transmission modes in FD-RAN.

1) Uplink Joint Reception: In uplink, each UE is served by its UBCS with a two-tier joint reception mode [6]. Specifically, all UEs transmit uplink signals on the same frequency band. Each UBS first combines signals from its multiple antennas and send the combined signals to the EC. Then, the EC uses corresponding channel state information (CSI) to jointly decode signals from UBSs within the same UBCS, obtaining UE's uplink data stream. This mode has the potential to reduce information redundancy and enhance transmission efficiency.

2) Downlink Cooperative Transmission: In downlink, there exist two potential cooperative transmission modes. The first is an intra-frequency mode [7], where multiple DBSs in the DBCS transmit signals to a UE on the same frequency band. The second is an inter-frequency mode [12], known as orthogonal transmission multi-connectivity (OT-MC), where multiple DBSs in the DBCS transmit signals to a UE on different orthogonal frequency bands. OT-MC provides multiple independent data streams for the UE, which can improve serving rates in a straightforward manner. Both two modes are subjects of ongoing research, and this article will focus on the OT-MC mode in following discussion.

FD-RAN PROTOCOL STACK

Figure 2 illustrates the protocol stack of FD-RAN. It can be seen that in FD-RAN, the EC possesses most of the protocol functions, while BSs retain only a few protocol functions.

1) Protocol Stack Split: The protocol stack split takes place in different layers for different planes. Specifically, in uplink data plane, we adopt the intra-PHY split referring to the Option 7 in 3GPP TR 38.801 [13]. Here, low PHY layer

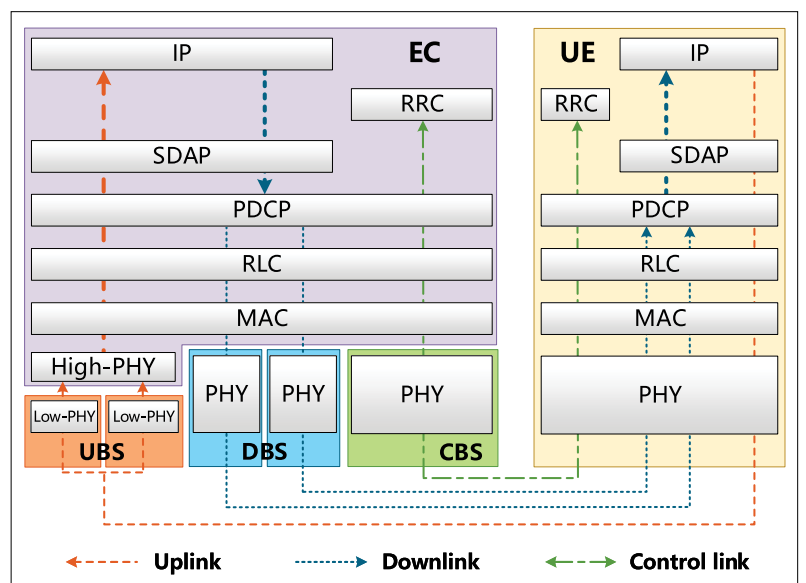


FIGURE 2. FD-RAN protocol stack architecture. Abbreviations: **IP**: Internet protocol; **RRC**: radio resource control; **SDAP**: service data adaptation protocol; **PDCP**: packet data convergence protocol; **RLC**: radio link control; **MAC**: medium access control; **PHY**: physical layer.

function resides in the UBS, while high PHY layer function and upper layers' protocols are located in the EC. Meanwhile, in downlink data plane, we adopt the medium access control (MAC)-PHY split referring to the Option 6 in [13]. Here, the entire PHY layer resides in the DBS, while upper layers' protocols are placed in the EC. Furthermore, the control plane's split mode is the same as downlink data plane.

2) Uplink Data Combination for Joint Reception: As shown by the orange line in Fig. 2, UBSs first combine multi-antenna signals at the low PHY layer upon receiving wireless signals from the UE. Then, the combined signals from multiple

UBSs are transmitted to the EC, where joint multi-UBS signal combination and decoding are performed at the high PHY layer. Afterward, the high PHY layer delivers the decoded data to upper layers for further processing.

3) Downlink Data Split and Aggregation for OT-MC: In the OT-MC mode, data plane traffic can be split into multiple streams in a specific protocol layer of transmitter, and then aggregated back in the mirrored protocol layer of receiver. As shown by the blue line in Fig. 2, data traffic in downlink FD-RAN split takes place in the packet data convergence protocol (PDCP) layer at the EC. Afterward, multiple independent data streams pass through lower layers and are eventually delivered to the PHY layers of different DBSs for signal transmission. Subsequently, multiple signals from multiple bands are received and processed by the UE through the PHY, MAC, and radio link control (RLC) layers. Then, multiple data streams are delivered to the PDCP layer for aggregation and the aggregated data stream is further delivered to upper layers.

MOBILITY MANAGEMENT KEY POINTS IN FD-RAN

This subsection introduces unique design ideas of the FD-RAN architecture, which pose challenges to traditional mobility management scheme but represent key points and advantages for our proposed HFMM.

1) Decoupled BS Association: In FD-RAN, traditional BSs are physically decoupled into CBS, UBSs, and DBSs, meaning that each UE needs to simultaneously maintain connections with at least three BSs. Thus, during mobility, UE will experience more connection changes with different types of BSs, compared to the all-in-one BS networking mode in 5G. So in HFMM, the signaling procedures for connecting and disconnecting from the three types of BSs need to be redesigned respectively.

Nevertheless, since the CBS is considered to have wide coverage, we can treat it as always connected with UE and only focus on connection changes of data BSs. With the control plane connection remaining unchanged, the signaling procedures of data plane connection changes can be greatly simplified, which helps alleviate signaling overhead.

2) Dynamic Multi-Connectivity: Different from the single connectivity mode in 5G, multi-connectivity is established as the default association mode in FD-RAN data plane. Since each UE is served by its own BCSs, the members of each BCS should dynamically change to adapt to UE mobility and channel conditions. Hence, in HFMM, the mobility management concept has been regarded as updating the BCS of UE, rather than handover between single source BS and target BS. So the conventional single-BS handover policy in 3GPP 5G protocols [9] is no longer applicable, meaning that HFMM requires a new decision-making scheme. Note that BCS updating refers to the process of adding/removing/replacing a BS to/from a UE's BCS. Additionally, the BCS can also remain unchanged.

3) On-Demand Service Provision: FD-RAN aims to provide on-demand services to users, striving to meet their QoS requirements as far as possible. At the same time, FD-RAN also attempts

to avoid blindly offering excessive services to UEs because this is not only meaningless, but also a waste of network resources (using too many serving BSs or too high transmission power), causing severe interference to other UEs.

In HFMM, mobility management controllers need to be able to perceive UE's service demands and update UE's BCS based on joint mobility and service demands, which puts forward higher requirements for the design of intelligent mobility management decision-making schemes.

HANDOVER-FREE FD-RAN MOBILITY MANAGEMENT FRAMEWORK

In this section, based on the above mentioned characteristics including complete BS decoupling and dynamic multi-connectivity, we propose a novel mobility management framework tailored for FD-RAN. Specifically, after a UE's power-up and network registration, dedicated BCSs (including UBCS and DBCS) are established for the UE to provide connectivity and services. As the UE moves or its service demand changes, the network will intelligently and dynamically updates the BCS members to ensure continuous, seamless, and on-demand services for the UE. In this process, UE does not suffer from hard handovers between individual BSs, instead, it is continuously served by its dedicated BCS. Here in FD-RAN mobility management, the BCS updating idea has replaced the traditional handover concept, so we refer to it as "handover-free" FD-RAN mobility management (HFMM).

In the following, we specify main procedures in HFMM, including UE initial access, UBCS initiating and updating, DBCS initiating and updating, which have been redesigned or newly designed for FD-RAN scenario. In addition, the detailed signaling procedures of BCS updating is also illustrated.

UE INITIAL ACCESS

After the UE powers on, it must establish a connection with EC before initiating data transmission. Initial access in HFMM involves phases such as cell search, time-frequency synchronization, and random access with the CBS. After that, the UE establishes a bidirectional control plane radio resource control (RRC) connection with the EC via the CBS. As a result, the UE acquires its cell radio network temporary identity (C-RNTI), and its RRC connection resides in the CCU. In the following discussion, we consider that the UE maintains the control plane RRC connection continuously. With the RRC connection in place, it will be straightforward for UE to establish data plane connections, get the BCS, and initiate both uplink and downlink data transmissions.

UBCS INITIATING AND UPDATING

After the UE initiates an uplink connection request, EC creates an initial UBCS for the UE using the large-scale fading based virtual service cluster selection method proposed in [6]. Then, the UBCS member will be updated dynamically according to UE mobility and channel conditions using the same method. Note that the UE always

transmits uplink signals omnidirectionally, which can be received by all UBSs. The updating of the UE's UBCS actually is that EC chooses which UBSs perform local decoding of the UE's signals and pass the local estimates to the EC for further centralized combining. So no matter how a UE's UBCS changes, it will not influence the uplink communication of other UEs since the inter-UE interference is constant.

The UBS members in a UE's UBCS are determined based on the marginal effect of adding serving UBSs. That is to say, for a UE, only those UBSs who can bring uplink rate improvement exceeding a certain threshold will be selected into its UBCS and serve it.

The UBCS updating process requires the EC to send control signalling to UBSs, which is efficient and low-latency, thanks to the wired optical fiber links between them. Moreover, the air interface signaling procedures of UBCS updating is quite simple. Specifically, because all UEs transmit uplink signals on the same given frequency band, there is no need for frequency synchronization between the UE and UBSs. Also, the signal sent by a UE will never be synchronously received by all serving UBSs in its UBCS because of the different distances between the UE and different UBSs. Therefore, strict time synchronization (such as time advance in 5G) between the UE and UBSs is

EC will make DBCS updating decisions, which has four types: DBS addition, DBS replacement, DBS removal and keeping still, as shown in Fig. 3.

not required. To compensate for that, a simple approach is to choose an appropriate length for the cyclic prefix to accommodate both the timing misalignments and channel delay spread. In conclusion, the updating of UBCS can be easily conducted under the control of the EC and do not involve signaling interactions with the UE. For the UE, UBCS updating is transparent and imperceptible.

DBCS INITIATING AND UPDATING

After the UE initiates a downlink connection request, EC creates an initial DBCS for the UE which only consists of one DBS with the largest reference signal received power (RSRP). Then, the DBCS updating process begins, during which the UE periodically measures the RSRP from each DBS and reports the measurement results along with its service rate demands to the EC via CBS. EC will make DBCS updating decisions, which has four types: DBS addition, DBS replacement, DBS removal and keeping still, as shown in Fig. 3.

The selection of which DBS to be added or removed follows the following rules. For the DBS

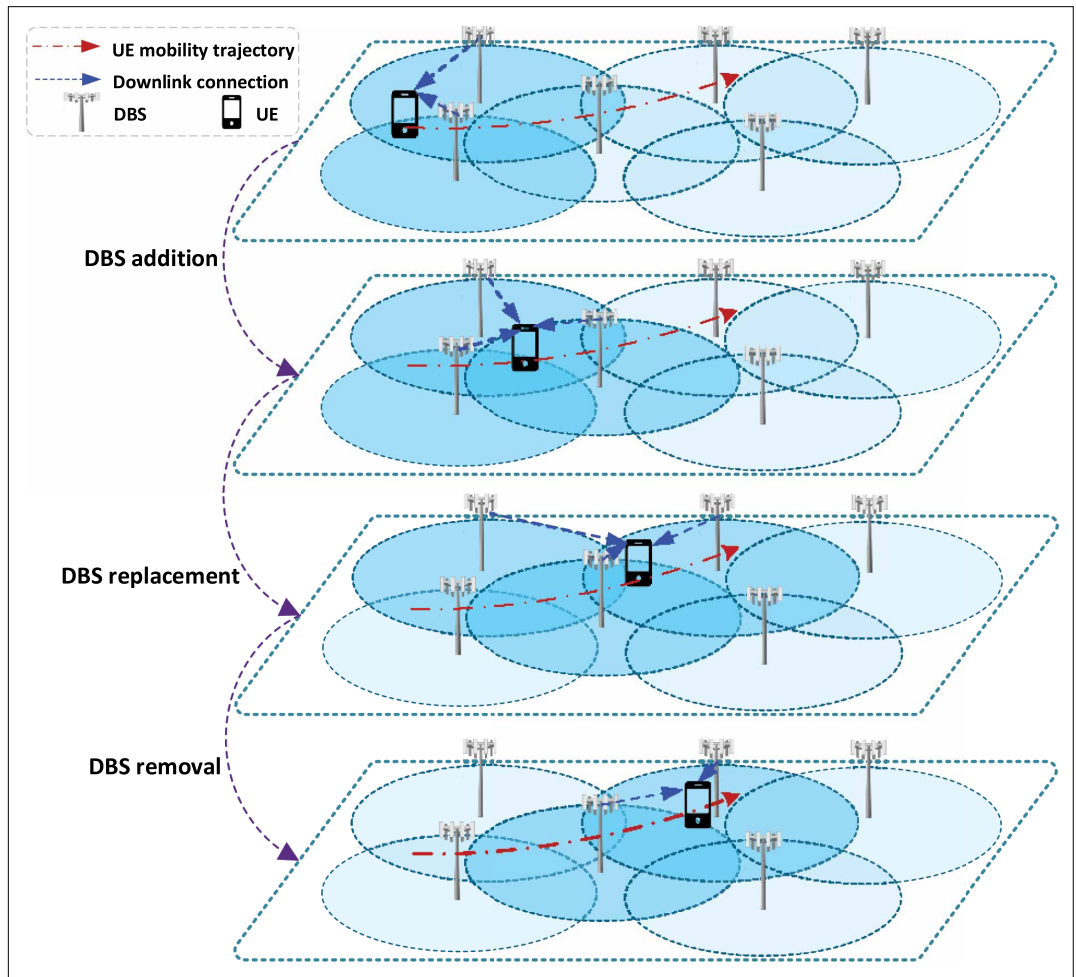


FIGURE 3. The diagram of DBCS updating process.

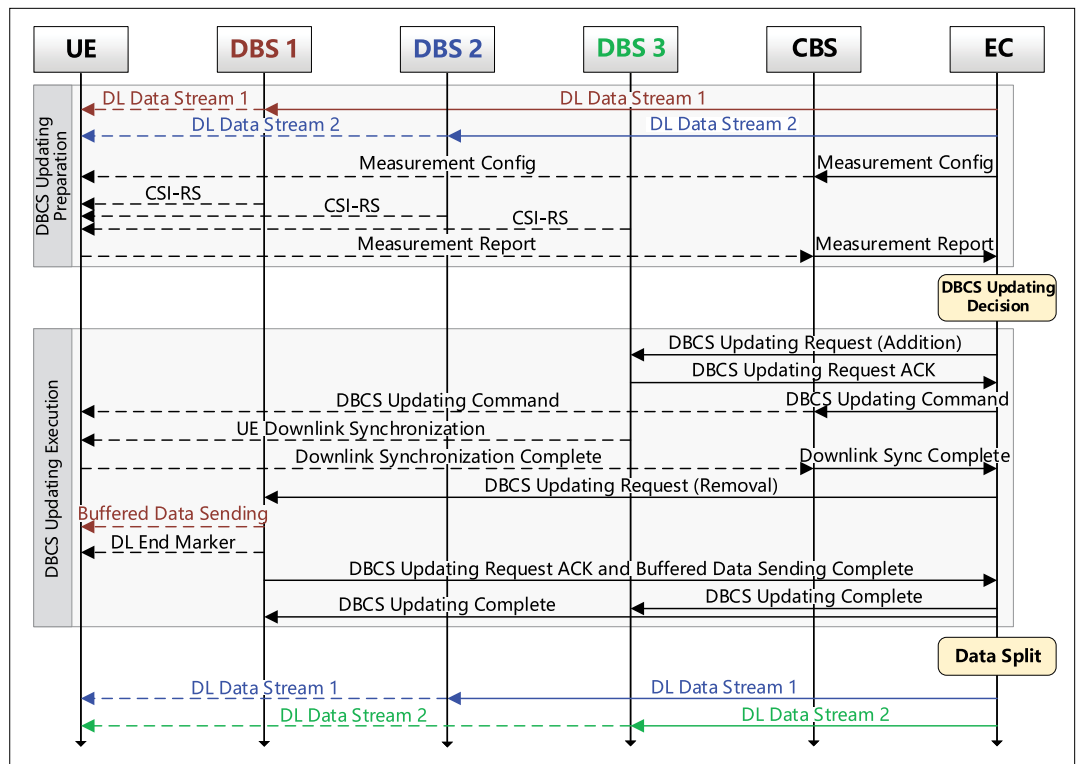


FIGURE 4. HFMM DBCS updating signaling procedures: DBS replacement.

addition operation, the DBS which has the largest RSRP measurement value outside the DBCS is chosen. For the DBS removal operation, the DBS which offers the lowest serving rate in the DBCS is chosen.

The number of DBSs in a DBCS has both upper and lower limits. The upper limit is an adjustable value imposed to prevent individual UE from consuming excessive network resources and causing increased network interference. The lower limit is a fixed value of 1 to ensure the continuous network connection for each UE. Note that to satisfy the constraints of the upper and lower limits of the DBCS scale, in some cases, certain DBCS updating type is forbidden. Specifically, for a particular UE, when the number of DBS in its DBCS is 1, the type of DBS removal is forbidden. When the number of DBS in its DBCS reaches the upper limit, the type of DBS addition is forbidden. So, how does EC make appropriate DBCS updating decisions? In the next section, we will present an AI-empowered FD-RAN downlink mobility management scheme as a case study.

Note that we employ distinct updating policies for UBCS and DBCS in HFMM framework because they involve different factors and objectives, which are due to the distinct collaborative transmission mechanisms in uplink and downlink.

BCS UPDATING SIGNALING PROCEDURES

Since the UBCS updating procedure is quite simple, we focus on the DBCS updating and describe specific signaling procedures of DBS replacement type in Fig. 4. It can be observed that the execution procedure of DBS replacement is actually accomplished by first adding one DBS and then

removing another DBS. Therefore, to simplify the narration, we omit the display of signaling procedures for DBS addition and DBS removal types, as each of them is part of Fig. 4.

In Fig. 4, the DBCS of the UE will be updated from including DBS 1 and 2 to DBS 2 and 3, and the specific signaling procedures are shown as follows:

- First, after the EC makes updating decision, a 'DBCS Updating Request (Addition)' including C-RNTI of the UE is delivered to DBS 3 for admission control.
- DBS 3 prepares radio resources and transmits a 'DBCS Updating Request ACK' to EC.
- A 'DBCS Updating Command' including the physical cell identity (PCID) of DBS 3 is delivered to the UE, instructing the UE to access DBS 3.
- The UE achieves time-frequency synchronization with DBS 3 by detecting and analyzing its synchronization signal block (SSB), and notifies EC by 'Downlink Synchronization Completes'.
- EC transmits a 'DBCS Updating Request (Removal)' to DBS 1, instructing it to stop serving the UE.
- DBS 1 sends buffered data and sends a 'DL End Marker' to the UE, instructing the UE to stop monitoring signal from it. Then, DBS 1 sends a 'DBCS Updating Request ACK and Buffered Data Sending Complete' to EC.
- EC sends 'DBCS Updating Complete' to DBS 1 and DBS 3, instructing that DBS 1 can release its radio resource and DBS 3 can start transmitting data.

Now the DBCS of the UE has been updated and has two members: DBS 2 and DBS 3.

Thereafter, data traffic from the core network is split into two streams at EC, and the two DBSs independently transmit the two data streams to the UE. To sum up, DBCS updating signaling on the RAN side has been simplified due to the continuous maintenance of control plane RRC connection. Furthermore, since the CDU in EC acts as the anchor point for the data plane, changes of DBCS are invisible to core network, resulting in savings of core network path update signaling overhead in traditional 5G handovers.

Note that in the DBCS updating execution phase, under the control of the EC, the UE will first establish connection (downlink time-frequency synchronization) with the target DBS (DBS 3), before disconnecting (stop receiving signal) from the source DBS (DBS 1). In that way, with the early established data plane connection between UE and target DBS, the downlink data stream that originally transmitted through the DBS 1 can seamlessly transfer to the DBS 3 and proceed transmitting. Thus, during the DBS replacement process, the network consistently maintains two downlink data streams for the UE and no service interruption occurs.

AI-EMPOWERED DOWNLINK HANDOVER-FREE MOBILITY MANAGEMENT IN FD-RAN: A CASE STUDY

In this section, we present a case study where a HDRL-based downlink HFMM scheme is employed to jointly perform DBCS updating decision and DBS link power control.

HDRL-BASED HFMM SCHEME

The first layer of our HDRL scheme is responsible for discrete DBCS updating decisions leveraging double deep Q-network (DDQN) algorithm. In order to provide UEs with finer-grained on-demand services, the second layer of our HDRL scheme is responsible for continuous downlink transmitting power control leveraging transformer-assisted soft actor-critic (TSAC) algorithm.

In the first layer DBCS updating decision, the EC creates a DDQN agent for each UE. Many previous works that use DRL for mobility management treat the UE-BS association as the action space. However, in multi-connectivity mode, there are numerous possible UE-BS association cases, leading to an excessively large DRL action space that can be difficult to converge. Therefore, we let the DDQN output one of the four types of DBCS updating decision, instead of explicit UE-DBS association configurations. Each agent independently observes the environment from the UE's report and obtains the state. The state is then fed into the DDQN network to determine the optimal action with the largest Q-value. The UE state, DBCS updating action, and reward function in the first layer are discussed as follows:

- UE State: The state of each agent includes UE's DBS access indicators, measured DBS RSRPs, and rate achieving ratio. The rate achieving ratio refers to the ratio of the UE's current serving rate to its rate demand.
- DBCS Updating Action: The action space of each agent consists of four types of DBCS

In each HDRL step, for each UE, DDQN layer first provides DBCS updating decision. After DBCS updating is performed and new UE-DBS association is determined, TSAC provides the transmitting power configuration for each UE-DBS link.

updating decisions: *Addition, Replacement, Removal and Remain*. Note that in certain cases, not all actions are valid due to the constraints of DBCS scale as explained in the section "DBCS Initiating and Updating." When performing a DBCS updating action, the selection rules of the target are as described in section "DBCS Initiating and Updating."

- Reward Function: The reward includes three components: rate bonus, DBCS updating cost, and multi-connectivity penalty, aiming to satisfy UE's rate demands, avoid frequent DBCS updating, and save network resources.

In the second layer UE-DBS link power control, the EC creates a TSAC agent for each UE-DBS link. Since multiple DBSs cooperatively serve the UE, the power control for links belonging to the same UE should be considered jointly. Considering that the number of serving DBSs for each UE may change, transformer encoder structure is well-suited to handle the multi-link joint power control, because it can handle dynamic-length vector sequences using padding and masking operations. The states of links belonging to the same UE will be concatenated into a sequence and padded to the maximum length, and then fed into the TSAC network to obtain optimal power actions for each link. The link state, power action, and reward function in the second layer are discussed as follows:

- Link State: The state of each agent includes the corresponding UE's DBS access indicators, measured DBS RSRPs, the link serving rate in last step, the rate demand and number of links of the corresponding UE, and so on.
- Power Action: The action of each agent is the offset value of DBS link power, which can be either positive or negative. The link's transmitting power is adjusted by adding the action offset value to the given default value.
- Reward Function: The reward function consists of two components: rate bonus and power cost, aiming to satisfy UE's rate demands while save transmitting power.

In each HDRL step, for each UE, DDQN layer first provides DBCS updating decision. After DBCS updating is performed and new UE-DBS association is determined, TSAC provides the transmitting power configuration for each UE-DBS link. If there is a situation where multiple DBSs need to be added or removed due to abrupt changes in UE's rate demand or channel conditions, the UE's DBCS will be continuously updated within a few consecutive steps, until its service demand is satisfied. The entire process will be completed rapidly.

The proposed HDRL-based scheme has good scalability because we leverage multi-agent technology in each layer of HDRL. As the number of

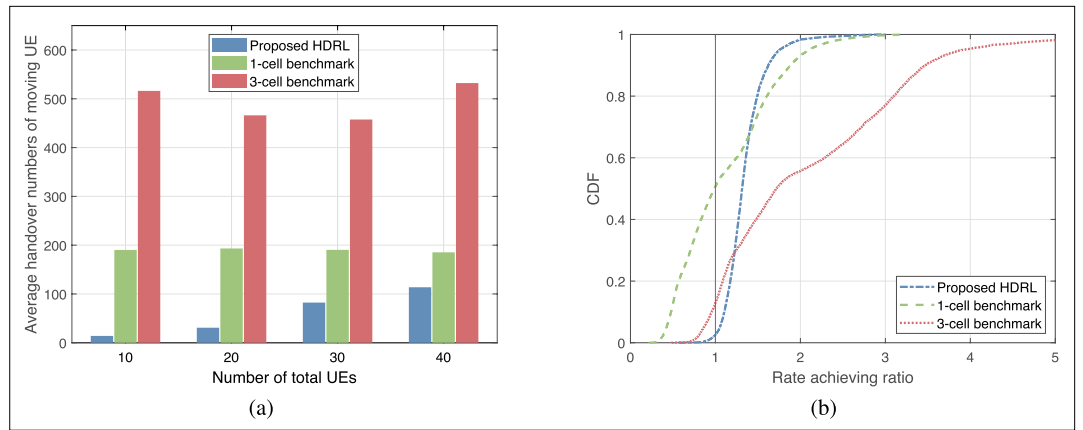


FIGURE 5. Performance comparison with benchmarks: a) CCS updating number. b) QoS dissatisfaction rate (demonstrated through rate achieving ratio).

UE increases, more and more agents are created in both layers, which can obtain neural network parameters directly from other homogeneous agents. Since each agent's action output depends on the policy and its own local observed state, the HDRL algorithm can admit a number of new agents while keeping the overall performance nearly unchanged. In this way, the proposed HDRL-based scheme can smoothly adapt to the dynamic in the number of UEs.

SIMULATION PARAMETER SETTINGS

To evaluate the performance of the proposed HDRL-based HFMM scheme, we implement simulations in Python 3.9 and PyTorch 1.12.0 environment. We consider a downlink-only FD-RAN scenario with seven DBSs deployed in hexagonal sites with inter-site distance of 519.6 m. Each DBS consists of three sectors (i.e., three cells) using different spectrum resources. Each cell has 10 sub-channels (SCs) with 2 MHz SC bandwidth. The DBSs operate at 5 GHz with 30 dBm of default link power. The link power offset value adjustment range is $[-5, 5]$ dBm. As for UEs, one half remains stationary, while the other half keeps moving following Gauss-Markov mobility model [14]. UEs are allowed to concurrently connect to a maximum of three cells, and each UE has its own dynamic rate demands generated from {15, 30, 45} Mbps. The channels between UEs and DBSs are generated based on 3GPP TR 38.901 UMa scenario [15].

The first layer DDQN structure is a four-layer fully connected neural network. The second layer TSAC structure is achieved by adding transformer encoder layers in front of the typical soft actor-critic (SAC) networks. The HDRL training process consists of 6 episodes where each episode has 5000 steps and each step represents a time length of 100 ms. After training, the HDRL networks are fixed, which will be used by agents to take optimal cell cooperation set (CCS, equal to DBCS) updating and power actions. All of the following simulation results are obtained in 5000-step testing episodes.

RESULTS AND DISCUSSIONS

In this subsection, we define two system performance indexes: CCS updating number and QoS dissatisfaction rate. CCS updating number means

the number of time when a UE takes an action other than *Remain*. QoS dissatisfaction rate means the time percent when 10-step-averaged rate achieving ratio of the UE is less than 1, where rate achieving ratio refers to the ratio of the UE's current serving rate to its rate demand.

We first compare two benchmarks with the proposed HDRL-based HFMM scheme. The first is a single-connectivity scheme called 1-cell benchmark, where each UE always connects to the cell with the highest RSRP. The second is a triple-connectivity scheme called 3-cell benchmark, where each UE always connects to three cells with the three highest RSRPs, and is served by OT-MC mode. In these two benchmarks, each UE's serving cell set is also called CCS, and the transmission power of all links is fixed at the default 30 dBm.

Figure 5a shows the comparisons of average CCS updating number among the three methods under different total UE numbers. We find that as UE number grows, UEs will experience more CCS updating in our HDRL-based HFMM scheme. However, regardless of the UE number, our scheme can greatly reduce CCS updating numbers compared with 1-cell benchmark and 3-cell benchmark, which mitigates control signaling overhead. Fig. 5b represents the cumulative distribution function (CDF) of the rate achieving ratio under 30-UE case. Here we hope the rate achieving ratio of UE is greater or equal to 1, but not too large. That is because that an excessively high rate achieving ratio usually means the UE has too many serving cells or the serving cells use too high transmission power, which wastes the network resources. By observing the proportion of rate achieving ratio less than 1, we can conclude that our scheme can achieve the lowest QoS dissatisfaction rate, which means it provides the best seamless and on-demand services for mobile UEs.

Next, we conduct two sets of ablation experiments to explore the relative impact of the two different layers (CCS updating layer and transmission power control layer) in proposed HDRL scheme on performance. In the ablation experiments, we name the proposed HDRL scheme as DDQN-TSAC algorithm, and introduce four comparing algorithms that can be divided into two groups, where each group corresponds to one set of ablation experiment.

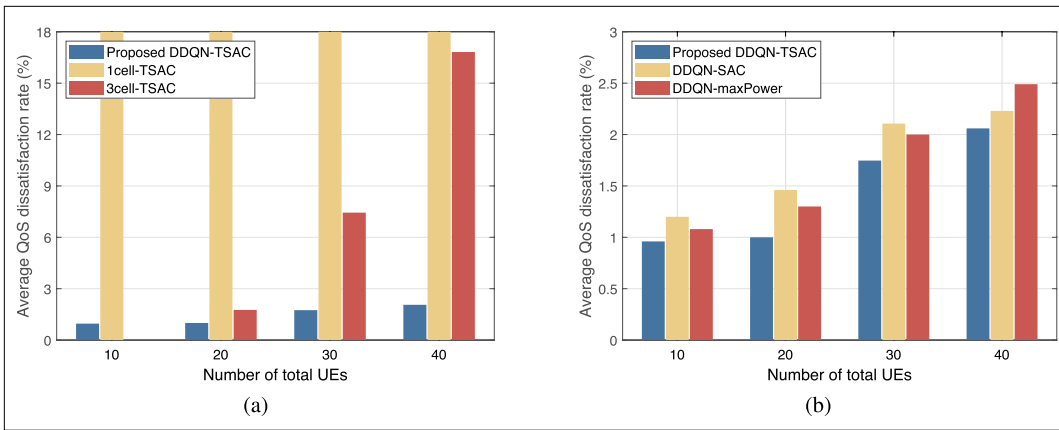


FIGURE 6. Ablation experiments: a) relative impact of different CCS updating policies and b) relative impact of different transmission power control scheme.

The first group consists of two algorithms called 1cell-TSAC and 3cell-TSAC, with their first layers respectively using the same CCS updating policies as the 1-cell and 3-cell benchmarks mentioned above. As for the second layer, both algorithms adopt the same power control scheme as used in proposed DDQN-TSAC. This group will be used to compare the relative performance impact of the DDQN-based CCS updating policy in the proposed DDQN-TSAC scheme.

Figure 6a shows the comparison of average QoS dissatisfaction rate among the three CCS updating policies, under the same TSAC-based transmission power control. Note that because QoS dissatisfaction rates of the 1cell-TSAC algorithm are too high (exceed 40%) under all cases, we do not fully present those data bars for ease of illustration. It can be observed that 1cell-TSAC algorithm performs the worst, while the proposed DDQN-TSAC markedly outperforms the 3cell-TSAC algorithm in most cases. That is because DDQN-TSAC algorithm can intelligently update UE's CCS instead of greedily forcing UE to connect too many cells, providing on-demand service while minimizing inter-cell interference, which is more friendly for poor-channel UEs. The only exception comes from the 10-UE case, where the large number of serving cells in 3cell-TSAC algorithm brings better service due to sufficient network resources.

The second group consists of two algorithms called DDQN-SAC and DDQN-maxPower, with their first layer using the same CCS updating policy as used in proposed DDQNT-SAC. As for the second layer, one algorithm replaces the TSAC algorithm in proposed DDQN-TSAC with a basic SAC algorithm for power control, while the other algorithm directly sets the power of each link to the maximum value (35 dBm). This group will be used to compare the relative performance impact of the TSAC-based transmission power control method in the proposed DDQN-TSAC scheme.

Figure 6b illustrates the average QoS dissatisfaction rate comparison among the three transmission power control schemes, under the same DDQN-based CCS updating policy. We can notice that the proposed DDQN-TSAC algorithm provides the best continuous services regardless of the number of UEs. This advantage arises

because in the power control layer of DDQN-TSAC algorithm, each agent (i.e., UE-cell link) belonging to the same UE will choose action considering states of all the UE's links through the transformer encoder module. This cooperation enables all agents within the same UE to appropriately adjust their transmission power instead of considering only the local state or choosing the fixed value.

Through ablation experiments shown in Fig. 6a and Fig. 6b, we can conclude that both the DDQN-based CCS updating layer and the TSAC-based power control layer in the proposed HDRL algorithm contribute positively to system performance. Relatively speaking, in our HDRL scheme, CCS updating policy (number of serving cells) has a greater impact on performance. The impact of transmission power control scheme is smaller, representing finer-grained adjustments.

CONCLUSION

In this article, we have explored the challenges and opportunities of mobility management in 6G FD-RAN and proposed a handover-free FD-RAN mobility management framework called HFMM, in which traditional handover concept is replaced by BCS updating for each mobile UE. We have provided an overview of the FD-RAN architecture and transmission mechanisms, and based on that we have elaborated the main procedures of HFMM including UE initial access and BCS updating. A case study applying the HDRL approach has been presented to demonstrate the applicability and potential of HFMM. In summary, we anticipate that this work will promote the development of mobility management for future 6G FD-RAN networks. In the future, we will continue to delve into the uplink part of HFMM and design AI-empowered algorithms for UBCS updating decision.

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