Kim, Junseok; Lee, Goodsol; Kim, Seongwon; Taleb, Tarik; Choi, Sunghyun; Bahk, Saewoong

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Two-Step Random Access for 5G System: Latest Trends and Challenges

Junseok Kim, *Member, IEEE*, Goodsol Lee, *Student Member, IEEE*, Seongwon Kim, *Member, IEEE*, Tarik Taleb, *Senior Member, IEEE*, Sunghyun Choi, *Fellow, IEEE*, and Saewoong Bahk, *Senior Member, IEEE*

***Abstract*—The 3rd Generation Partnership Project (3GPP) finalized Release 15 specifications for the 5th Generation New Radio (5G NR) in June 2018. In Release 16, the 3GPP worked on not only technical improvements over the previous release but also the introduction of new features. One of the new features is the use of Two-step Random Access Channel (2-step RACH) that enhances 4-step random access with respect to radio resource control connection setup and resume procedures. In this article, we first look into details of 2-step random access defined in the 3GPP Release 16, and briefly introduce recent literature related to 2-step random access. Second, we present challenges of the above random access schemes. Among the challenges, we focus on how a User Equipment (UE) performs self-uplink synchronization with the next-generation Node B (gNB) to resolve preamble collisions, which occur when multiple UEs transmit the same preamble. Specifically, we propose a framework that helps the UE estimate the Timing Advance (TA) command using a deep neural network model and to determine the TA value. Finally, we evaluate the proposed framework in terms of the accuracy of TA command estimation, the inference time, and the battery consumption.**

***Index Terms*—5G new radio, 2-step random access, timing advance, and machine learning.**

I. Introduction

The 5th Generation (5G) system will be the foundation technology for business innovation in various vertical industries such as smart factories, cars, and smart cities. In June 2018, the 3rd Generation Partnership Project (3GPP) finalized Release 15 specifications, which are the first 5G New Radio (NR) standard including non-standalone and standalone modes. In April 2019, mobile operators in South Korea and the United States launched commercial 5G services. In June 2020, the 3GPP completed Release 16 including not only technical improvements of Release 15 specifications but also the introduction of new features. In Release 17, 3GPP is working on the new features for a wide variety of industry verticals and non-terrestrial access systems to build out to be substantially more versatile than 4G Long Term Evolution (LTE).

One of the new features in Release 16 is the use of Two-step Random Access Channel (2-step RACH). The 3GPP Radio Access Network (RAN) working groups specify 2-step random access covering both physical layer and higher layer. 2-step random access potentially offers benefits in the following two scenarios [1]. First, for burst transmission of small packets, simple random access is attractive for reducing the significant overhead of Radio Resource Control (RRC) connection setup and resume procedures [2]. Second, for the NR Unlicensed spectrum (NR-U), reducing the steps of random access helps decrease the latency for connecting a User Equipment (UE) to a next-generation Node B (gNB) since they perform a listen-before-talk procedure for connection step.

In this article, we present the details of 2-step random access in 5G NR, namely 2-step Contention-Based Random Access (CBRA), which suffers from *preamble collision* when many UEs try channel access. This is because many UEs compete for the limited number of preambles on the same time-frequency resource called Physical Random Access Channel (PRACH) resource. We briefly introduce the existing 2-step random access schemes proposed to solve the *preamble collision* problem [3], [4]. Each scheme has pros and cons, so we present the challenges of the random access schemes. As a means to solve the *preamble collision* problem, we focus on Timing Advance (TA) command estimation of a UE for self-uplink synchronization with the gNB.

Therefore, we propose a framework that helps a UE determine its own TA value. In the proposed framework, an edge RAN controller trains a simple Deep Neural Network (DNN) model on large data consisting of features (Reference Signal Received Power values) and labels (TA commands). Each UE estimates the TA command using machine learning, and determines a TA value.

In summary, this article includes:

- a comprehensive overview of 2-step CBRA defined in the 5G NR and recently studied 2-step random access schemes
- a discussion of the challenges of 2-step random access schemes
- a framework for TA command estimation using a DNN model and TA value determination for each UE to resolve the *preamble collision* problem.

Corresponding authors: Seongwon Kim; Saewoong Bahk.

J. Kim is with System LSI, Samsung Electronics, Gyeonggi-do, Korea (e-mail: junseok.kim@samsung.com).

G. Lee, and S. Bahk are with the Department of ECE and INMC, Seoul National University, Seoul, Korea (e-mail: gslee2@netlab.snu.ac.kr, sbahk@snu.ac.kr).

S. Kim is with Vision AI Labs in SK Telecom, Seoul, Korea (e-mail: s1kim@sktair.com).

T. Taleb is with the Department of Communications and Networking, School of Electrical Engineering, Aalto University, Finland. He is also with the Faculty of Information Technology and Electrical Engineering, Oulu University, and with the Department of Computer and Information Security, Sejong University, Seoul, Korea (e-mail: tarik.taleb@aalto.fi).

S. Choi is with Advanced Communications Research Center at Samsung Research, Samsung Electronics, Seoul, Korea (e-mail: sungh.choi@samsung.com).

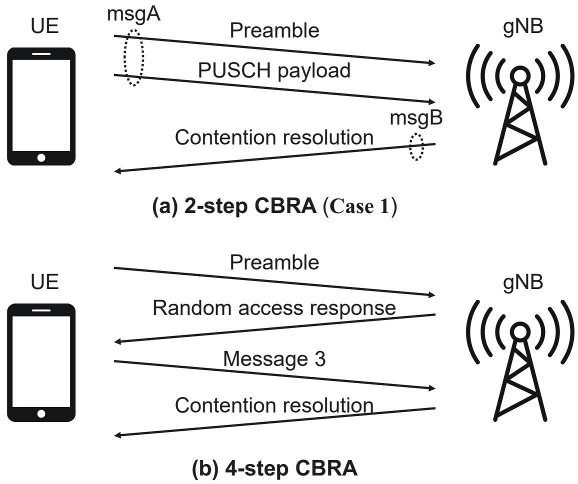


Figure 1. CBRA in 5G NR.

II. 2-Step Random Access

In the 5G NR Release 15, CBRA has the same steps as 4-step CBRA in 4G LTE. To reduce latency, the 5G NR Release 16 and recent literature simplify the existing CBRA procedures from four steps to two steps. We overview the 2-step CBRA procedures defined in the 5G NR and two random access procedures in [3], [4].

A. Overview of 2-Step CBRA

The RAN working group addresses a simplified 2-step random access as a work item. This item proposes a common design for unlicensed spectrum as well as licensed spectrum. This article focuses on the 2-step CBRA in the licensed spectrum. As shown in Fig. 1, 2-step CBRA has the advantage of reducing latency by simplifying the existing 4-step CBRA that carries preamble and payload separately. Message A (msgA) contains a preamble on PRACH and a payload on Physical Uplink Shared Channel (PUSCH). The payload corresponds to the message 3 in 4-step CBRA, which is the first scheduled uplink transmission [5]. After transmitting a msgA with a preamble, a UE waits for a message B (msgB) from the gNB on Physical Downlink Shared Channel (PDSCH) for the configured window. The gNB takes different actions depending on its reception status of msgA.

- **Case 1** The gNB detects the preamble from the UE and successfully decodes the payload. It notifies the UE of contention resolution by sending a successful Random Access Response (RAR) with a TA command which is an integer value greater than or equal to zero.
- **Case 2** The gNB detects a single preamble but fails to decode the payload. Using the preamble reception time, it sends back a fallback RAR to the UE with the TA command and an uplink grant for the payload retransmission.
- **Case 3** The gNB detects multiple identical preambles from UEs. There is no fallback RAR because the gNB is unable specify the preamble reception time of each UE. Therefore the gNB transmits a backoff indication to UEs that will attempt random access again.
- **Case 4** The gNB fails to detect the preamble. There is no RAR to the UE.

The UE upon receiving the RAR successfully completes the 2-step CBRA. Upon receiving the fallback RAR, the UE falls back to 4-step CBRA with message 3 transmission (i.e., payload retransmission). In **Case 3**, the UE performs a backoff procedure and retransmits msgA after waiting for the length of the configured window called *RAR window*. In **Case 4**, the UE retransmits msgA after waiting for the length of *RAR window*. If 2-step CBRA could not succeed even when the UE transmits the msgA 'M' times, the UE would fall back to 4-step CBRA that starts from the preamble transmission.

B. Channel Structure for msgA

Different from the first step in the 4-step CBRA, msgA in 2-step CBRA contains payload as well as preamble. Therefore, the channel structure for msgA should be newly defined, which includes mapping between a preamble on a PRACH resource and a time-frequency resource for the PUSCH payload, time-frequency resource size of PUSCH, and so on [6].

2-step CBRA uses the preamble format specified in Release 15 [7]. The msgA preamble set is different from the 4-step CBRA preamble set, but the both preamble sets can be transmitted through the same RACH Occasion (RO) or separate ROs. Fig. 2 represents an example of the channel structure for msgA. Two ROs exist in a RACH slot, and each RO uses 32 preambles for 2-step CBRA. The beam association rule between Synchronization Signal Block (SSB) and RO of 4-step CBRA [7] is used for 2-step CBRA as follows. The gNB associates an SSB index with its own RO and/or preamble. Different SSB indexes indicate different downlink beams of the gNB or different reception beams of the gNB in the case of uplink transmission. Fig. 2 shows that a set of 16 preambles out of 32 preambles is used to represent a specific beam. For example, if the UE transmits preamble 5 in the second RO, the gNB uses the beam corresponding to SSB #2 to receive the payload of the msgA.

The payload transmission consists of PUSCH Occasions (POs) which span multiple Orthogonal Frequency Division Multiplexing (OFDM) symbols and Physical Resource Blocks (PRBs). Each PO consists of multiple PUSCH Resource Units (PRUs), and each of which contains the following fields:

- PRU ID
- Multiple OFDM symbols and PRBs for uplink transmission
- Association with preamble(s) of a PRACH resource
- Modulation and coding scheme
- Uplink power control related parameters
- Demodulation Reference Signal (DMRS) port and DMRS sequence.

Fig. 2 shows that one PO includes two PRUs, and occupies four RBs in the frequency domain and seven symbols in the time domain. One PRU is associated with one or more preambles of a PRACH resource, i.e., preamble ID(s) of a

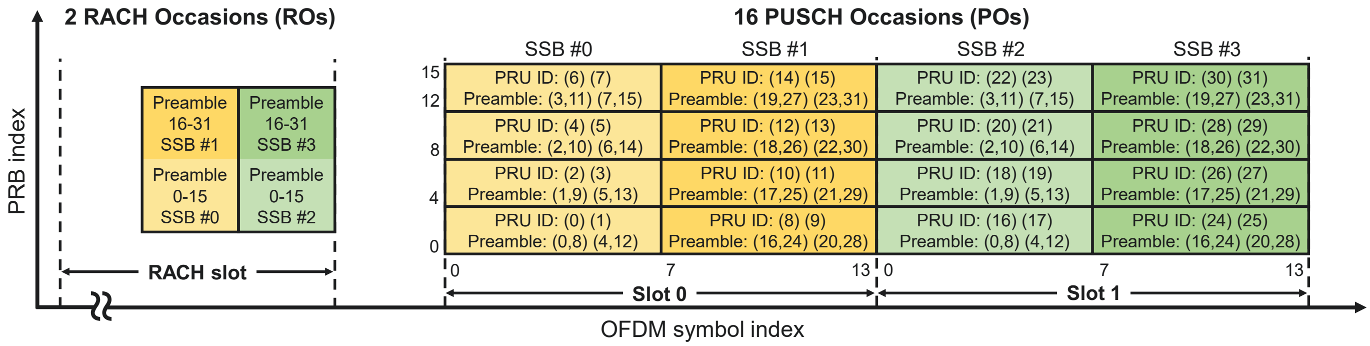


Figure 2. Example of the channel structure for msgA: mapping between preamble IDs and PRU IDs, and resource size of each PO.

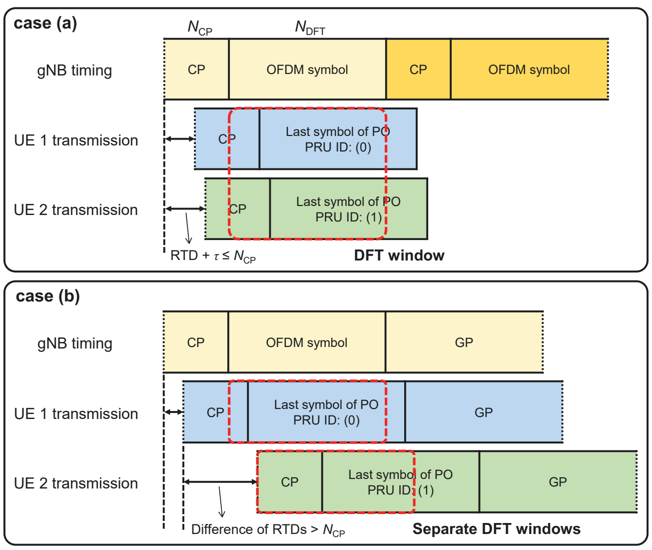


Figure 3. Two cases of the payload reception timing at the gNB.

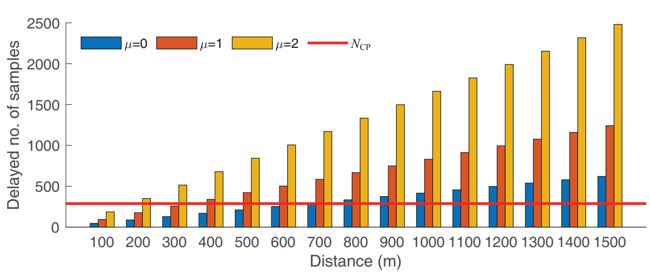


Figure 4. Number of delayed samples vs. distance from the gNB and numerologies.

specific RO. There are two types of resource mapping between preambles of PRACH resource and a PRU: many-to-one and one-to-one mapping. Fig. 2 shows an example of many-to-one mapping and the mapping ratio, where the number ratio of preamble IDs to a PRU is two. Preambles 0 and 8 transmitted in an RO for SSB #0 are mapped to PRU ID 0.

C. TA Handling for the Payload

TA value (N_{TA}) is a negative time offset for the UE to control uplink transmission timing. An adequate TA value makes uplink transmission better aligned with the symbol timing at the gNB. In 2-step CBRA, the gNB determines a TA command (T_{A}) based on the reception timing of the msgA preamble. Then, the UE calculates a TA value using the TA command and its numerology (μ), i.e., $N_{\mathrm{TA}}(T_A, \mu)$ [8].

On the other hand, the TA value for the payload of the msgA is set to zero [6]. The gNB receives uplink transmissions with different delays depending on the distance between the UE and the gNB. Basically, OFDM systems mitigate multipath interference with the help of the Cyclic Prefix (CP) between two adjacent OFDM symbols. The case (a) of Fig. 3 shows that the sum of Round Trip Delay (RTD) and delay spread (τ) for each UE is less than or equal to the CP. So the gNB can decode OFDM symbols from different UEs transmitted at the same time. Otherwise, Inter-Symbol Interference (ISI) occurs due to delayed OFDM symbols. Thus, the RAN working group added optional Guard Period (GP) to the end of each PO illustrated in the case (b) of Fig. 3. The GP ranges from 0 to 3 symbols [6].

Fig. 4 represents the number of delayed samples according to the distance from the gNB and numerologies. When the numerologies are zero, one, and two, the subcarrier spacing values are 15, 30, and 60 kHz, respectively. We easily calculate the number of delayed samples by rounding up the sum of RTD and τ divided by the sampling time, i.e., $\lceil(\mathrm{RTD}+\tau)/\text{sampling time}\rceil$ where τ is 93.325 ns, which is the root mean square delay spread of 3D-Urban Macro (UMa) model used in [3]. The sampling time is the inverse of the sampling rate, i.e., $1/(N_{\mathrm{DFT}}\times\text{subcarrier spacing})$ where N_{DFT} is Discrete Fourier Transform (DFT) size, i.e., 4096. The CP length (N_{CP}) is 288 in the unit of the number of samples, indicated by the red line in Fig. 4. As the subcarrier spacing values increase, we can find that environments where the maximum distance values from the gNB (or coverage) are over 700, 400, and 200 m, need the GP.

D. 2-Step Random Access in Recent Literature

In 2-step CBRA, when multiple UEs try channel access, the probability that different UEs use the identical preamble in the same PRACH resource increases, resulting in the *preamble* *collision* problem. We divide this problem into two cases. First, if more than two UEs at a similar distance from the gNB transmit the same preamble using the same RO, the payload transmission would fail even if their preamble transmissions are successful (**Case 2**). We refer to this case as the *undetected collision* problem. Second, if multiple UEs at different distances from the gNB transmit the same preamble using the same RO, the gNB detects multiple identical preambles. In this case, the gNB fails to determine the TA command for each UE (**Case 3**). This case is called the *detected collision* problem.

We have proposed two types of 2-step random access to resolve the *preamble collision* problem. First, in the contention resolution-based random access [3], the gNB allocates a unique context ID to each UE. The UE selects and transmits a preamble from a specific preamble set, using a specific PRACH resource mapped to the context ID (one-to-many mapping between a subset of PRACH resources and context IDs). Upon receiving the preamble, the gNB transmits multiple RARs to candidate UEs that could have sent the preamble. This scheme completes random access by exchanging only two messages. In this way, we can solve the *undetected collision problem*. In addition, when a *detected collision* occurs, the gNB uses the TA command for each UE that was stored during the UE's first access. However, the shortcoming is that unnecessary RAR transmissions to all candidate UEs increase with the number of UEs. Also, the scheme considers only fixed UEs.

Second, the proposed scheme in [4] enables 2-step random access by representing a preamble ID by bits and dividing the bits into two parts: ID part and information part. ID part is dedicated to the single UE, and information part conveys the purpose of random access and buffer status of the UE. As the existing 64 preambles (corresponding to 6 bits) cannot cover both information and unique IDs for many UEs, we have proposed a preamble sequence generation method. This scheme does not suffer from both the *undetected collision* and *detected collision* problem because the gNB can not detect the same preamble at the same time. The limitation is that the preamble generation is possible only in an ultra-dense network scenario where the cell density is higher than 1000 cells/km^2 [4].

III. Challenges of 2-Step Random Access

In this section, we present the challenges of 2-step random access introduced in this article.

A. Preamble Allocation

For the preamble of msgA, 2-step CBRA uses a disjoint set of preambles from 4-step CBRA out of 64 preambles, so a preamble allocation problem arises. For preamble allocation, we consider the incidence ratio between 2-step CBRA and 4-step CBRA in a specific cell. Similar preamble allocation problems have been studied in our previous work. In [3], a subset of preambles is allocated to contention resolution-based random access considering the number of UEs and their traffic characteristics. In [4], each UE is assigned a unique ID part and multiple preambles have the same ID.

B. Resource Mapping for msgA

5G NR has two types of resource mapping between preamble ID(s) of a specific RO and a PRU: many-to-one and one-to-one. Many-to-one mapping maps two or more preamble IDs of a specific RO to one PRU ID, while one-to-one mapping maps one preamble ID of the specific RO to one PRU ID. We select one of two configurations according to the number of UEs simultaneously attempting 2-step CBRA. If the number is small, many-to-one mapping is suitable for efficient use of PUSCH resources. Otherwise, one-to-one mapping is appropriate. The use of many-to-one mapping increases the probability that different UEs use the same PUSCH resource to send their payloads, resulting in a collision.

C. DFT Operation in gNB

2-step CBRA uses the TA value of zero for the msgA payload. Thus, the GP may exist at the end of the PUSCH payload according to the parameters such as the numerology, delay spread, and coverage of the gNB. The gNB determines where to locate DFT windows in the payload including the GP using the preamble reception timing. For instance, in the case (b) of Fig. 3, the gNB measures the difference in timing of preamble reception between UE 2 and UE 1 greater than the CP length, and so performs additional DFT operation. Meanwhile, if the UE could transmit the msgA payload by well determining the TA value for the area it is located at, the GP would be unnecessary. Then, the gNB takes advantage of resources to transmit and receive other data.

D. Detected Collision Problem

The *detected collision* problem occurs when UEs at different distances from the gNB send the same preamble. There are two works that solve the *detected collision* problem [3], [9]. In [3], however, there is a limitation that the approach cannot be applied to mobile UEs. This limitation can be avoided as each UE estimates the TA command, and selects and transmits a preamble from a specific set of preambles corresponding to the estimated TA command. Upon receiving the preamble from the specific preamble set, the gNB implicitly notices the TA command of the UE. The authors in [9] resolve the *detected collision* problem by transmitting separate RARs under the assumption that all UEs calculate their own TA value. Applying the approach in [9] to 2-step CBRA, we can reduce the preamble collision probability. Therefore, we propose the self-uplink synchronization framework, aiming to overcome these limitations in the next section.

IV. Self-Uplink Synchronization Framework

The self-uplink synchronization framework that we propose in this section helps a UE determine a TA value within the timing error limit defined in 5G NR [10].

A. Overview

In the proposed framework, the UE estimates the TA command using a DNN model and Reference Signal Received Power (RSRP) values. The input of the DNN is RSRP values

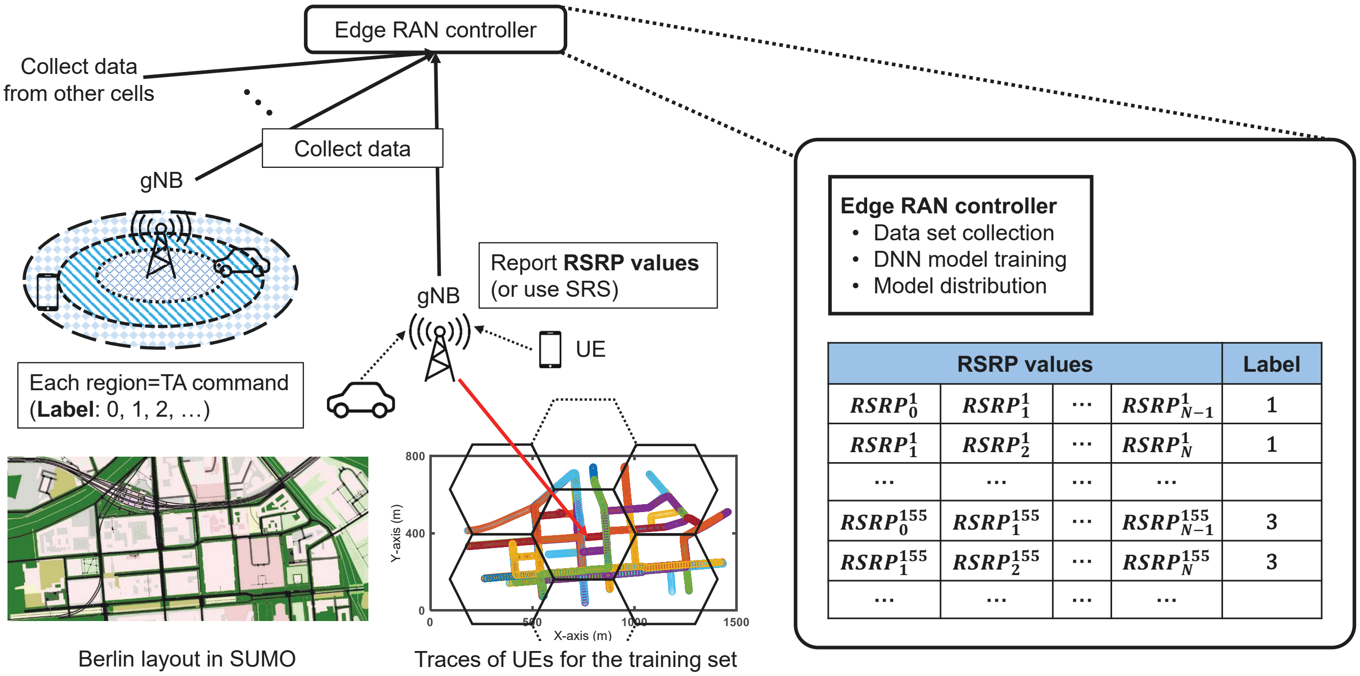


Figure 5. Overview of the training procedures with the mobility model and topology.

and the output is an estimated TA command ($\hat{T}_A$). As shown in Fig. 5, the edge RAN controller collects labeled data sets from gNBs, consisting of UEs' RSRP values and corresponding TA commands. After training the DNN with data sets, the edge RAN controller distributes the DNN model to UEs through the gNBs.

B. Overall Procedures

The procedures for estimating the TA command based on RSRP values are as follows:

- A UE in the RRC connected state [2] periodically reports its RSRP values to the connected gNB. Then, the gNB periodically sends a set of N RSRP values and the TA command (label) for each UE to the edge RAN controller. The label is the same as the TA command reported when the gNB received the latest RSRP value for a specific set. In Fig. 5, $RSRP_j^i$ represents the j-th RSRP value of UE i.
- With sufficiently collected labeled data, the edge RAN controller trains the DNN model. We consider a network with three hidden layers and one output layer. Each hidden layer is 200-way fully-connected. The outcome of each hidden layer is followed by *ReLU* activation function. The output layer uses *softmax* activation whose output is a probability vector for the TA command. We select a cost function with cross-entropy, and apply the Adam optimization algorithm for training.
- The edge RAN controller notifies each UE of the information about this model such as number of layers, weight matrix, and so on. It also updates the DNN model regularly or when needed.
- After receiving the model information, the UE obtains the estimated TA command from the DNN model and N RSRP values.

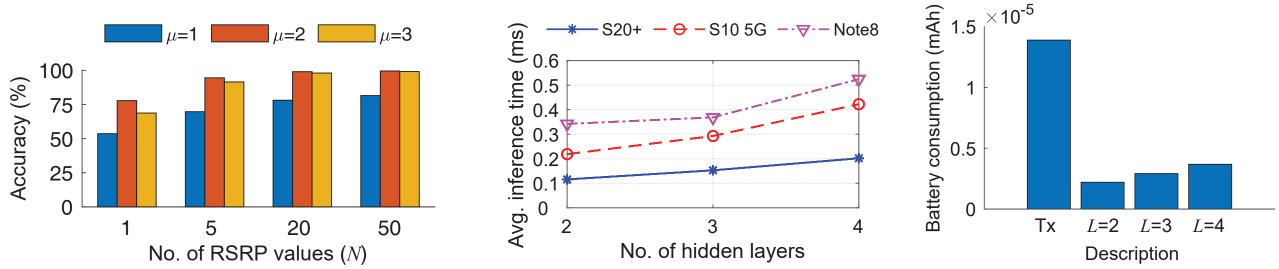
We consider the gNB to collect RSRP values directly by measuring the received power of the Sounding Reference Signal (SRS) using channel reciprocity, i.e., without RSRP reporting from UEs .

C. Performance Evaluation

Simulation environments: We use OpenStreetMap (OSM) provided by Simulation of Urban Mobility (SUMO), linked to the actual map information [11]. SUMO can reflect real environments including vehicle movements and traffic lights. The total time of tracing is one hour, and the number of UEs is 155. For the channel model, we create the path loss and shadowing following 3D-UMa model, and consider the fast fading channel model generated using ITU-R IMT UMa model used in [3]. Channel environments, i.e., Line-Of-Sight (LOS) or Non-LOS (NLOS), are stochastically determined, depending on the distance between UEs and the gNB. We use the hexagrid topology for the seven cell deployment as shown in Fig. 5. The innermost cell is placed in the center of the trace map of UEs and the inter-site distance is 500 m. We consider frequency range 1 [7] because an application using small packets is appropriate for 2-step random access.

Measurement model: As assumed in [12], we simplify the RSRP formula by considering the assumption of the physical layer that the channel is flat within a PRB. This means that all resource elements within the PRB have the same power. The RSRP value is calculated as the sum of all PRBs' powers for the synchronization signal divided by the number of PRBs [13]. The period for the RSRP update is 5 ms, which is the shortest period for synchronization signals [7].

TA granularity: When the subcarrier spacing is 15 kHz, the TA granularity is 0.52 μs [8]. Because the TA value should be twice the propagation delay, the distance corresponding to the TA granularity is 78 m ($= 0.52 \times 3 \times 10^2/2$). When



(a) Accuracy (b) Average inference time (c) Battery consumption

Figure 6. Performance of the DNN model.

the subcarrier spacing values are 30 kHz and 60 kHz, the corresponding distances are 39 m and 19.5 m, respectively. When the DFT size is 4096, the TA granularity is given by 32 time samples regardless of subcarrier spacing. The value 32 is obtained by dividing the TA granularity by the sampling time for subcarrier spacing.

Accuracy: When measuring the accuracy of TA command estimation, we consider the UE initial transmission timing error less than or equal to $\pm T_e$, where T_e is the timing error limit value [10]. When the subcarrier spacing values are 15, 30, and 60 kHz, the corresponding timing error limit values are 24, 40, and 80 time samples, respectively. For the subcarrier spacing values of 30 and 60 kHz, because the timing error limit values are greater than the TA granularity, the use of TA values corresponding to different TA commands from the notified TA command is tolerated. Fig. 6(a) shows the accuracy of TA command estimation according to the subcarrier spacing and the number of RSRP values (N) for TA command estimation. As the number of RSRP values increases, estimation accuracy increases. We find that past RSRP values help with classification, and estimation accuracy converges when N is 50. The estimation accuracy increases to 99.6% and 99.1% for 30 and 60 kHz subcarrier spacing values, respectively, while it is 81.5% for 15 kHz due to its short timing error limit value.

Inference time: We observe the inference time according to the number of hidden layers to see how the complexity of DNN model affects mobile devices. In Fig. 6(b), as the number of hidden layers (L) increases, the average inference time increases. In the case of the most recent device, i.e., Galaxy S20+ released in 2020, the average inference time is 0.15 ms when L is set to three in the proposed framework. Because this value is smaller than the slot length when the subcarrier spacing is 60 kHz (0.25 ms), the UE can estimate the TA command in one slot after receiving the latest reference signal.

Battery consumption: Using "Batterystats" tool included in the Android framework, we observe the battery consumption (mAh) of the CPU over time for an application that runs the DNN model. We measure the battery consumption of Galaxy S20+ during 100,000 iterative inference operations. Through the measurement, we obtain the discharge current using battery consumption and application end time, which is (battery consumption)×3600/(application end time). The discharge current for inference operation is 65.66–68.76 mA. Then, we can obtain the battery consumption for one inference operation using the discharge current and average inference time of Fig. 6(b). Fig. 6(c) shows the battery consumption for transmission of UE and one inference operation according to L. The discharge current of the UE for transmission is 100 mA [14]. When L is set to three in the proposed framework, the UE can estimate the TA command by consuming about 21% of the battery consumption for transmission.

D. Future Research Perspectives

We summarize future research directions as follows.

Performance enhancement: To further reduce symbol errors caused by ISI at the gNB when multiple UEs transmit the msgA payload with their estimated TA values, we can apply a rule-based approach combined to the DNN model. This approach helps a UE determine its TA value more precisely by taking the probability distribution of the TA command obtained from the DNN model into account.

Generalization: To make the model easily adapt to new environments, we may adopt meta-learning [15], also known as "learning to learn". Specifically, by collecting different data sets for diverse network environments and applying a meta-learning method, e.g., Model-Agnostic Meta-Learning (MAML) [15], we can quickly initialize the model to a state trainable with a few data sets.

Network performance: We need to evaluate network performance considering the accuracy of TA command estimation. For example, the proposed framework enables 2-step CBRA to be applied with the approach in [9]. This helps to reduce the preamble collision probability. Therefore, we should observe network performance in terms of latency of uplink packet transmission. To this end, we can take into account the performance of DNN model shown in Fig. 6.

Real-world environments: The Android Application Programming Interface (API) provides the RSRP and TA command (*CellSignalStrengthNr* class), so we can collect data sets through measurements in real-world environments. We should consider whether a data set is useful, taking into account its characteristics such as the time interval for updating RSRP values during measurements.

V. Concluding Remarks

In 5G NR, the 3GPP included 2-step CBRA to further improve latency for channel access compared with 4-step CBRA.

We introduced the newly defined messages and corresponding channel structure for 2-step CBRA. We presented 2-step random access schemes proposed in the recent literature to tackle the *preamble collision* problem that occurs when many UEs try 2-step and 4-step CBRA. We listed the challenges of the 2-step random access schemes, and proposed the self-uplink synchronization framework that allows a UE to determine its TA value to solve the *preamble collision* problem, using the DNN model. Lastly, we summarized the research directions to improve the performance of the proposed framework and generalize it for real world environments.

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Junseok Kim (junseok.kim@samsung.com) is a Staff Engineer at System LSI Business in Samsung Electronics, Gyeonggi-do, Korea. He received the B.S. degree in Electronics and Electrical Engineering from Chung-Ang University in 2011, and Ph.D. degrees in Electrical and Computer Engineering from Seoul National University (SNU) in 2020.

Goodsol Lee (gslee2@netlab.snu.ac.kr) is currently pursuing the Ph.D. degree with the Department of Electrical and Computer Engineering from SNU. He received the B.S. degree in Electrical and Computer Engineering from SNU in 2018.

Seongwon Kim (s1kim@sktair.com) is a Research Engineer at Vision AI Labs in SK Telecom, Seoul, Korea. He received the B.S. degree in Electrical Engineering from the Pohang University of Science and Technology (POSTECH) in 2011, and the M.S. and Ph.D. degrees in Electrical and Computer Engineering from SNU in 2013 and 2017, respectively.

Tarik Taleb (tarik.taleb@aalto.fi) is a professor at Aalto University, Espoo, Finland. He is the founder and director of the MOSA!C Lab (www.mosaic-lab.org). Prior to that, he was a senior researcher and 3GPP standards expert at NEC Europe Ltd., Germany. He also worked as an assistant professor at Tohoku University, Japan. He received his B.E. degree in information engineering, and his M.Sc. and Ph.D. degrees in information sciences from Tohoku University in 2001, 2003, and 2005, respectively.

Sunghyun Choi (sungh.choi@samsung.com) is a Senior Vice President and Head of the Advanced Communications Research Center at Samsung Research, Samsung Electronics, Seoul, Korea. He is currently heading researches and standardization for 6G, B5G, and IoT connectivity. He was a professor at the Department of Electrical and Computer Engineering, SNU, from Sept. 2002 to Aug. 2019. He received his B.S. (summa cum laude) and M.S. degrees in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST) in 1992 and 1994, respectively, and received Ph.D. at the Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor in September 1999.

Saewoong Bahk (sbahk@snu.ac.kr) is a professor at SNU, Seoul, Korea. He is President of the Korean Institute of Communications and Information Sciences (KICS). Prior to joining SNU, he was with AT&T Bell Laboratories as a member of technical staff from 1991 to 1994. He received B.S. and M.S. degrees in electrical engineering from SNU in 1984 and 1986, respectively, and a Ph.D. degree from the University of Pennsylvania in 1991.