R-SplitC: Collision Minimization for Cellular Communication in Unlicensed Spectrum

Jihoon Kim, Jaehong Yi, and Saewoong Bahk

Abstract: **The 3rd generation partnership project (3GPP) has standardized 5G new radio in unlicensed spectrum (NR-U) that uses a wide unlicensed spectrum as an alternative solution to the insufficient bandwidth problem of the existing NR. NR-U has a listen-before-talk (LBT) operation similar to the carrier sense multiple access with collision avoidance (CSMA/CA) operation of Wi-Fi. It allows nodes to transmit only after LBT success. NR-U suffers from the collision issue because its channel access mechanism is similar to that of Wi-Fi. Wi-Fi solves the collision problem through the request-to-send/clear-to-send (RTS/CTS) mechanism. However, NR-U has no way of solving the collision problem. As a result, NR-U suffers severe performance degradation due to collisions as the number of contending nodes increases. In this paper, we propose to use an extended and split reservation signal (RS) for reservation in NR-U that consists of front RS and rear RS and design a new collision minimization scheme, termed *R-SplitC*, that contains two components: new RS structure and contention window size (CWS) control. The new RS structure helps to minimize collisions in NR-U transmissions, and CWS control works to protect the performance of other communication technologies such as Wi-Fi. We mathematically analyze and evaluate the performance of our scheme and confirm that *R-SplitC* improves network throughput by up to 99.3% compared to the baseline RS scheme without degrading Wi-Fi performance.**

Index Terms: **Collision, LTE-LAA, NR-U, reservation signal, unlicensed spectrum.**

I. INTRODUCTION

As mobile data demand has increased rapidly in recent years, all demands cannot be satisfied with the limited licensed band. The 3rd generation partnership project (3GPP) first standardized long-term evolution (LTE) licensed-assisted access (LTE-LAA) in 3GPP Release 13 by developing LTE that uses only the existing licensed band to share unlicensed bands [1]. The standardization of enhanced LAA (eLAA) in 3GPP Release 14 and further enhanced LAA (feLAA) in 3GPP Release 15 has been continued [2], [3]. The standardization of the new radio (NR) in unlicensed band (NR-U), which is an NR operating in the unlicensed band, is underway, a key technology for 5G [4], [5]. Research on cellular communication operating in the unlicensed band is active recently, and the actual deployment is gradually progressing. In Chicago, cellular operators such as AT&T, Verizon, and T-Mobile have installed numerous LTE-LAA eNBs [6].

Cellular communication technologies in unlicensed spectrum proposed by 3GPP operate in a distributed manner. That is, each device goes through a channel sensing process, and only when the channel is idle, it can start transmission. This operation suffers the collision problem due to simultaneous transmissions as the number of competing devices increases. Wi-Fi solves the collision problem by sending and receiving short control frames called request-to-send/clear-to-send (RTS/CTS) frames.

However, NR-U shows a different situation. After completing the LBT, an NR-U gNB has two options. The NR-U gNB can wait without any transmission (self-deferral) or transmit a dummy signal called reservation signal (RS) until the next initial mini-slot starting point.[1] The gNB starts data transmission at the next initial mini-slot starting point. We consider only the environment that gNBs transmit an RS since the gNB cannot occupy the channel well in a high traffic environment when it uses a self-deferral approach. The length of RS lies between 0 and 71 μs, depending on the time the LBT is completed.[2] Because an NR-U gNB starts data transmission only at the orthogonal frequency division multiplexing (OFDM) symbol boundary and its decoding time is longer than that in Wi-Fi, it cannot exchange short frames like RTS/CTS on Wi-Fi in a short time. This means that NR-U has limitations in solving the collision problem.

In this paper, we first propose a collision reduction scheme, termed *R-Split*, that minimizes the collision probability in NR-U transmissions by extending RS duration and splitting a legacy dummy RS into two short signals: front RS and rear RS. It places an idle gap of short inter-frame space (SIFS) duration between front RS and rear RS to allow the transmitting gNB to sense the channel. Only the gNB that senses the channel idle during this gap can transmit its rear RS and following data frames. Each gNB randomly selects the position of the idle gap.

R-Split reduces collisions, thereby reducing the contention window size (CWS) of each gNB. The reduced CWS of each gNB may harm Wi-Fi performance compared to the baseline scheme that uses the legacy RS. To avoid this problem, we add a CWS control procedure to *R-Split* to increase the CWS of each gNB and name it as *R-SplitC*.

The main contributions of this paper are three-fold:

- We propose *R-Split* that minimizes collisions by extending

Manuscript received June 3, 2021; approved for publication June 9, 2021. This paper is specially handled by EIC and Division Editor with the help of three anonymous reviewers in a fast manner.

This work was supported by Korea Environment Industry & Technology Institute(KEITI) through Exotic Invasive Species Management Program, funded by Korea Ministry of Environment(MOE). (2021002280002)

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Digital Object Identifier: 10.23919/JCN.2021.000020

[1] The next initial mini-slot starting point is the next OFDM symbol boundary except for the last OFDM symbol boundary in a slot.

[2] This range is for 30 kHz subcarrier spacing.

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RS duration and splitting a legacy RS into two short signals. *R-Split* puts a randomly selected SIFS idle gap between two short signals for an RS transmission, which helps gNBs reduce collisions.

- We improve *R-Split* to *R-SplitC* by adding a CWS control procedure that protects Wi-Fi traffic by increasing the CWS of each gNB, which has been reduced by *R-Split*.
- We mathematically analyze *R-Split* and *R-SplitC* in an NR-U only environment and validate our modeling through simulation. We confirm that *R-SplitC* improves the throughput of NR-U significantly compared to the baseline scheme without adversely affecting Wi-Fi performance.

The rest of this paper is organized as follows. We present related work and preliminaries in Section II. We propose our proposed schemes in Section III. In Sections IV and V, we present the modeling of the proposed schemes and demonstrate their performance through extensive simulations. Finally, we conclude the paper in Section VI.

II. RELATED WORK AND PRELIMINARIES

A. Related Work

There have been many studies on the performance of LTE-LAA and NR-U. In particular, there are many studies on the coexistence performance of LTE-LAA and Wi-Fi. In [7]–[11], the authors increase the coexistence performance by modifying LBT operation. In [12], the authors adapt the maximum channel occupancy time (MCOT) of LTE-LAA to the aggregated medium access control protocol data unit (A-MPDU) duration of Wi-Fi for fair channel occupancy.

Many LTE-LAA studies mathematically analyze the throughput performance based on Bianchi model [17]. In [18], the authors analyze the LTE-LAA throughput performance considering LTE-LAA frame structure, including the ending partial subframe (EPS). In [19]–[24], the authors analyze the coexistence performance of LTE-LAA and Wi-Fi. We conduct the performance analysis of our proposed scheme based on [17], [18] with the consideration of NR-U frame structure.

Some studies consider the collision problems in LTE-LAA and NR-U. In [13], the authors raise a problem of modulation and coding scheme (MCS) underestimation due to collisions. The authors solve the problem by distinguishing the underestimated channel quality information (CQI) from normal CQI. However, this work does not decrease collisions. In [14], the authors find that if a collision between LTE-LAA and Wi-Fi which uses RTS/CTS occurs, the fairness problem arises because only LTE-LAA nodes successfully transmit. The authors solve the problem by modifying RS. However, they only consider the coexistence between LTE-LAA and Wi-Fi which uses RTS/CTS. In [15], the authors propose an LBT technique for collision resolution of NR-U in addition to the operation of [14]. However, RS duration in NR-U is too short for collision resolution due to the mini-slot. Our work reduces collisions that cause MCS underestimation and solves the collision problem between NR-U nodes by extending RS duration and designing an RS frame structure with various priorities. It does not incur any harmful impact on Wi-Fi traffic regardless of RTS/CTS operation.

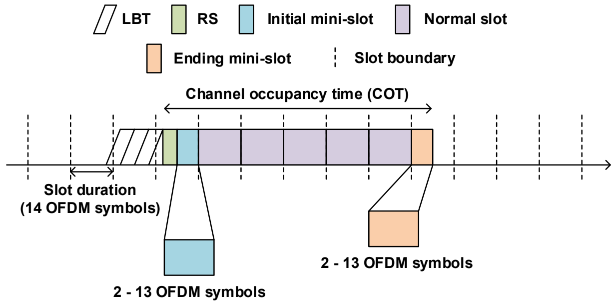

Fig. 1. NR-U frame structure.

B. NR-U

NR-U is first standardized in 3GPP Release 16 and uses licensed and unlicensed bands together or unlicensed bands only, unlike NR that uses only the licensed band [4]. In the unlicensed band, an NR-U gNB starts transmission only after completing the LBT operation. It can occupy the channel up to MCOT defined in the specification. In the case of priority class 3, MCOT is 8 ms when other communication technologies exist, and 10 ms otherwise [4].

C. Listen-before-talk (LBT)

An NR-U gNB starts transmission after completing one of the two types of LBT: Category 4 LBT and 25 μs LBT. First, Category 4 LBT is an operation similar to Wi-Fi's CSMA/CA operation. The gNB first senses the channel for a defer period of arbitrary inter-frame space (AIFS) duration. If the channel is idle during the AIFS, the gNB starts backoff operation. The gNB randomly selects a backoff counter value in the range of [0, CW]. If 80% or more of Hybrid ARQ feedback of the starting slot of the previous transmission of the gNB is NACK, the gNB increases the CWS. Otherwise, the gNB resets the CWS to the minimum value. The range of the CWS value depends on the priority class of the transmitted data. In this paper, we mainly consider best effort traffic that has the CWS range in [16, 32, 64].

Second, 25 μs LBT is an operation enabling transmission without a backoff operation when the channel is idle for 25 μs. Most of transmissions of the gNB use Category 4 LBT and only intermittent transmissions such as discovery reference signals use 25 μs LBT.

D. Reservation Signal and Mini-slot

Fig. 1 shows the NR-U frame structure. When a gNB succeeds in LBT operation, it transmits an RS until the next mini-slot starting point. The RS is a dummy signal whose length varies depending on the end time of LBT and informs other devices of the channel occupancy of the gNB. NR-U starts data transmission at OFDM symbol boundaries. If the next OFDM symbol boundary after LBT success is a slot boundary, the gNB transmits a normal slot after the RS. Conversely, if the next OFDM symbol boundary after LBT success is a OFDM symbol boundary (i.e., not a slot boundary), the gNB transmits an initial mini-slot after the RS. Each initial mini-slot consists of

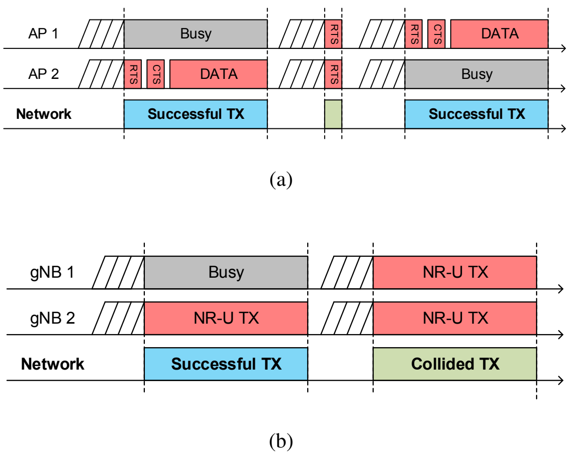

Fig. 2. Collision cases in the unlicensed band: (a) Collision between Wi-Fi with RTS/CTS and (b) collision between NR-U.

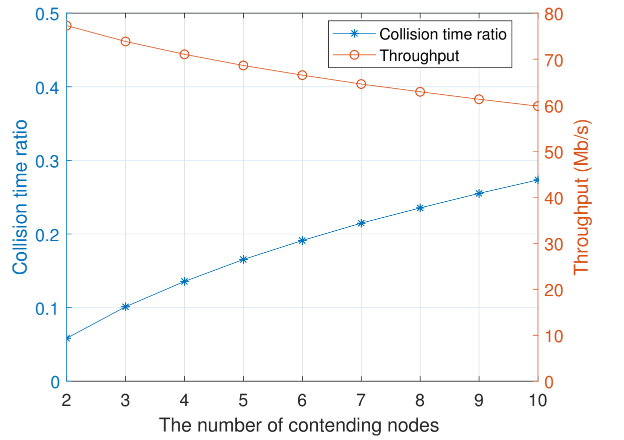

Fig. 3. Collision time ratio and throughput according to the number of contending nodes.

2–13 OFDM symbols.

To transmit a data frame of maximum length not exceeding MCOT, NR-U uses 12 types of ending mini-slot (EMS). Each EMS consists of 2–13 OFDM symbols. In this paper, we name each of the 13 EMS types as EMS type i ($i = 1, \cdots, 13$), where EMS type 1 is a transmission that does not use EMS. As i increases, EMS type i uses ending mini-slot with i OFDM symbols.

E. Wi-Fi

Wi-Fi has a channel access mechanism of CSMA/CA. For best effort traffic, the maximum CWS in Wi-Fi is 1024. Wi-Fi uses A-MPDU for a long transmission with its maximum duration of 5.484 ms in IEEE 802.11ac [26]. For RTS/CTS operation, a sender first transmits an RTS frame before data transmission. After decoding the RTS frame, the receiver transmits a CTS frame to the sender. Then, a data frame is transmitted only when the sender successfully decodes the CTS frame. If the RTS frame collides with other transmissions, the receiver fails to decode the RTS frame and does not send the CTS frame. The sender restarts CSMA/CA operation with increased CWS after CTS timeout.

F. Collision between NR-U Transmissions

When the channel is saturated, more collisions occur with the number of contending nodes. In the case of Wi-Fi using RTS/CTS, no CTS response means that a collision has occurred. However, in the case of NR-U, there is no way of detecting collisions during a transmission. NR-U gNBs transmit data as close to the length of MCOT as possible when the traffic is saturated. Therefore, if a collision occurs, all gNBs involved in the collision waste time because no node can successfully transmit during the collision. Figs. 2 (a) and (b) show examples of collisions in Wi-Fi and NR-U, respectively. From a network point of view, colliding transmissions cause more time wasted in NR-U than in Wi-Fi. With the number of collisions, the efficiency in NR-U is significantly worse than that in Wi-Fi.

NR-U has a mechanism to increase CWS to minimize collisions. However, the mechanism cannot completely resolve collisions. Fig. 3 shows our simulation results of the collision time ratio and network throughput in an NR-U only network with the number of gNBs.[3] As the number of gNBs increases, the collision time ratio increases, and the network throughput decreases. The results show that the damage caused by collisions increases with the number of contending nodes despite the CWS increase mechanism.

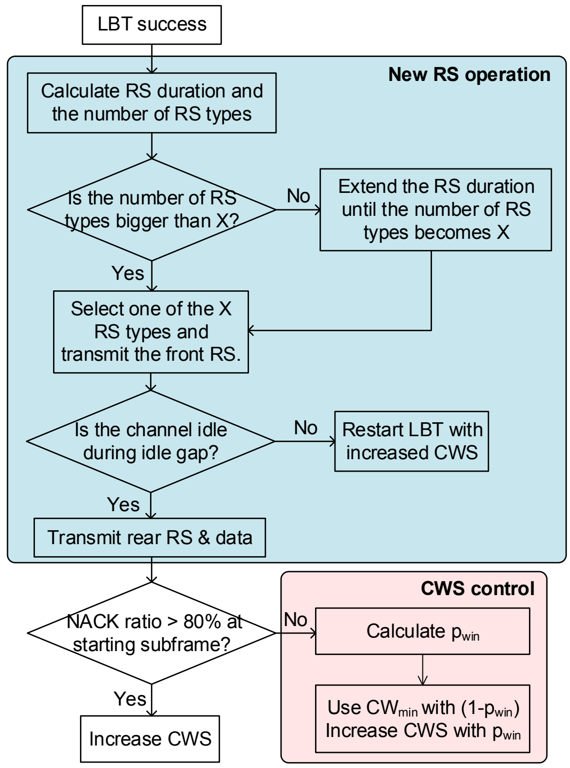

Fig. 4. Flow chart of *R-SplitC*.

III. PROPOSED SCHEME

In this section, we propose *R-Split* that aims to enhance NR-U performance by minimizing collisions. We also propose *R-SplitC* by adding an operation to *R-Split* to protect the transmission of other communication devices such as Wi-Fi. Fig. 4 shows the flow chart of *R-SplitC* that consists of two main features: new RS operation and CWS control. *R-Split* uses the new RS operation only without CWS control. The new RS operation consists of two procedures: RS extension and RS split. RS extension extends RS duration until a gNB has the desired number of RS types and reduces data parts to maintain COT shorter than MCOT. RS split consists of three procedures: front RS transmission, 16 μs idle gap sensing, and rear RS transmission, where 16 μs is SIFS duration used for collision avoidance. There are a TX/RX turnaround time and a backoff slot in the 16 μs idle gap.[4]

Assume that there are three gNBs transmitting RSs after simultaneous LBT success. Each gNB transmits a front RS with a length randomly chosen within the limited length. Then it performs channel sensing for the idle gap of 16 μs. If gNB 2 has the highest priority among the three (i.e., the longest front RS length), gNB 2 detects the channel idle during its idle gap. Then only the gNB 2 is allowed to transmit its rear RS and data slots.[5]

Since each of gNBs 1 and 3 has a shorter front RS length than gNB 2, they sense the channel busy during the idle gap and cannot transmit their rear RS. They restart LBT with increased CWS. The increased transmission success rate of each gNB contributes to lowering its CWS. The CWS decrease of the gNB degrades Wi-Fi performance. To compensate for excessive CWS reduction owing to the new RS operation, each gNB performs the CWS control operation to increase its CWS. For the CWS control, each gNB calculates the conditional probability that its previous successful transmission was resulted from winning a collision. With this probability, it increases its CWS.

A. New RS Structure

When a gNB succeeds in LBT, it calculates the RS duration, d_{RS}, which is the duration from the time that the gNB succeeds in LBT to the next mini-slot starting point. Using d_{RS}, the gNB obtains the number of RS types, n_{RS}, that the gNB can have, as

$$n_{RS} = \left\lfloor \frac{d_{RS}}{d_{\text{SIFS}}} \right\rfloor, \tag{1}$$

where d_{SIFS} is SIFS duration. n_{RS} ranges from 0 to 4 because the maximum RS duration is 71 μs when subcarrier spacing is 30 kHz. The n_{RS} in this range is not sufficient for collision resolution. Therefore, the gNB sets a desired n_{RS} value guaranteed for each transmission (X) and extends the RS to obtain this value.

There are two RS extension methods for guaranteeing X. When the expected RS duration can be satisfied by reducing the length of the initial mini-slot, the length of the initial mini-slot is reduced and the RS is extended accordingly. If not, the current initial mini-slot is changed to RS, and the first normal slot is changed to an initial mini-slot, and then RS is additionally extended.

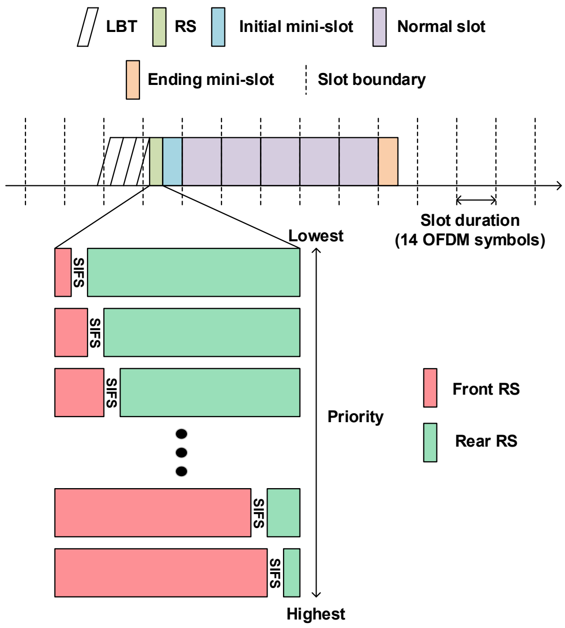

Fig. 5. New RS structure with a fixed RS duration.

Fig. 5 shows our new RS structure with a fixed RS duration. There is no overlapped idle gap between the two different RS types. We give a different priority to each RS type. As shown in Fig. 5, the shorter the front RS duration, the lower the priority of RS type. The gNB randomly selects one RS type that becomes the gNB's priority and accordingly transmits its front RS. If there is no collision, the gNB transmits its rear RS and data slots after having the idle gap of SIFS duration.

When gNBs with different priorities collide during the front RS transmission, the gNB with the highest priority continues to transmit its front RS (which length is longer than that of a gNB with a lower priority) and sense the channel for the SIFS duration. The channel will be idle because the other gNBs with lower priorities have stopped transmission after transmitting their front RS. Then the gNB is allowed to transmit its rear RS and following data slots. This means that the gNB with the highest priority wins the collision, so the collision is resolved.

If there are multiple gNBs with the highest priority in a collision, they all transmit their rear RS and data slots because they have an idle gap of SIFS duration at the same time, sensing the channel idle together. Due to the collision, no gNB receives an ACK, and the collision is not resolved.

B. CWS Control

The new RS operation reduces collisions by helping each gNB to avoid collisions. For the same example of colliding three gNBs, in the baseline scheme, each gNB receives a NACK and increases its CWS. In our proposal, gNB 2 wins the collision without noticing there was a collision. After gNB 2 succeeds in transmission, it is supposed to use CW_{min} next time, and gNBs

[3] The collision time ratio is a ratio of collision time to the total simulation time.

[4] If the TX/RX turnaround time is shorter than 7 μs, 16 μs idle gap is possible for channel sensing. In [27], the TX/RX turnaround time is shorter than 2 μs.

[5] No other channel sensing-based device can occupy the channel for the 16 μs idle gap. At least an idle period of 25 μs is needed to occupy the channel newly [16].

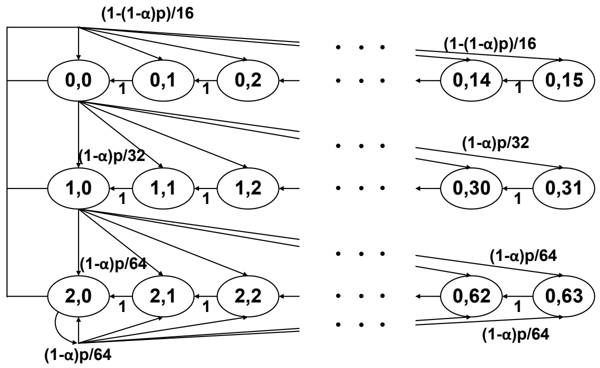

Fig. 6. An example of the Markov chain model for *R-Split*.

1 and 3 increase their CWS because they have detected a collision. Our CWS control allows the winner to increase its CWS as much as close to the CWS in the baseline scheme. That is, gNB 2 calculates the probability p_{win} that there was a collision and it was the winner. With this probability, gNB 2 increases its CWS, which helps to achieve a good balance between NR-U gNBs and Wi-Fi stations.

To get p_{win}, a gNB first finds out the number n of contending nodes in the saturated channel. Through primary synchronization signal (PSS) and secondary synchronization signal (SSS) decoding, the gNB counts the number of cell IDs of each NR-U transmission. Then we get n and obtain p_{win} as

$$p_{win}(k, n_{RS}) = \frac{\sum_{i=1}^{n-1} \binom{n-1}{i} \tau^i (1-\tau)^{n-1-i} p_i(k, n_{RS})}{\sum_{i=0}^{n-1} \binom{n-1}{i} \tau^i (1-\tau)^{n-1-i} p_i(k, n_{RS})}, \tag{2}$$

where k is the priority of the gNB, τ is the measured transmission probability of the gNB defined in Bianchi model [17], and $p_i(k, n_{RS})$ is the probability that the gNB has higher priority than all the other i transmitting gNBs. $p_i(k, n_{RS})$ equals the probability that each of i gNBs selects an RS with a priority lower than k. We define $p_i(k, n_{RS})$ as

$$p_i(k, n_{RS}) = \left(\frac{k-1}{n_{RS}}\right)^i. \tag{3}$$

$p_{win}(k, n_{RS})$ is the conditional probability that the gNB receives an ACK as a collision winner when receiving an ACK. If the gNB receives an ACK, it increases its CWS with probability $p_{win}(k, n_{RS})$ and uses CW_{min} with probability $(1 - p_{win}(k, n_{RS}))$.

IV. PERFORMANCE ANALYSIS

In this section, we mathematically analyze the performance of *R-Split* and *R-SplitC* in an NR-U only network.

A. Throughput Analysis for R-Split

We analyze the performance of *R-Split* based on [17], [18], [25]. We assume that 1) saturated traffic, and 2) ideal channel (i.e., zero bit error rate (BER)). According to [18], in the LTE-LAA only network, the EPS type of the current transmission and a minimum backoff counter value after the current transmission (bc_{min}) determine the EPS type of subsequent transmission. This feature is the same in the NR-U only network. The only difference between the NR-U only network and the LTE-LAA only network is that there are 13 types of ending mini-slots for NR-U and 7 types of EPS types for LTE-LAA.

We propose a modified Markov chain model to deal with the collision resolution effect of the new RS structure. Then, we derive the steady state EMS type distribution and the network throughput of the system. Fig. 6 shows an example of the modified Markov chain model for *R-Split* when the channel access priority class is 3.[6] In the modified Markov chain model, each state (i,j) represents the backoff stage i and the backoff counter value j [17]. p is the probability that the transmission of a gNB results in a collision, the same as in Bianchi model. α is the probability that the gNB selects an RS with the highest priority among the gNBs involved in a collision, and any other gNB does not select the same highest priority. In our scheme, a gNB that participates in a collision and wins the collision uses the minimum CWS next. Due to this property, we replace p with $(1-\alpha)p$ (i.e., reduced collision probability) in the modified Markov chain model.

We use an iterative procedure to get α in the modified Markov chain model. First, we select α_{init} as an input value. Then, we get τ and p by solving the system of equations below.[7]

$$\tau = \frac{2(1-2\bar{\alpha}p)}{(1-2\bar{\alpha}p)(W+1) + \bar{\alpha}pW(1-(2\bar{\alpha}p)^m)}, \tag{4}$$

$$p = 1 - (1 - \tau^{n-1}), \tag{5}$$

where $\bar{\alpha} = 1 - \alpha_{\text{init}}$. We obtain (4) and (5) from the modified Markov model based on [17]. W is the minimum CWS, m is the maximum backoff stage, and n is the number of contending nodes. Using the results of the modified Markov chain model, we get the bc_{min} distribution.

We define a new bc_{min} distribution of *R-Split* in (6) based on [25]. We consider three cases for bc_{min}: Successful transmission, resolved collision, and unresolved collision. P_{tr} is the probability that at least one gNB transmits at a generic slot, P_s is the probability that only one gNB transmits when the channel is busy. P_i is the probability that i gNBs transmits simultaneously in a generic slot. S_v, B_v, and C_v are the sum of backoff counter value distribution from v to CW_{max} of a gNB that is in the state of successful transmission, idle, and collision, respectively [25]. S_v is defined as

$$S_v = \sum_{l=v}^{\text{CW}_{\text{max}}} h_l, \tag{7}$$

where h_l is the probability that a gNB station has a backoff counter value l right after its successful transmission. h_l is defined as

$$h_l = \begin{cases} \frac{1}{\text{CW}_{\text{min}}+1}, & 0 \le l \le \text{CW}_{\text{min}}, \\ 0, & l > \text{CW}_{\text{min}}, \end{cases} \tag{8}$$

[6] When the channel access priority class is 3, the minimum CWS is 16, and the maximum CWS is 64 [1].

[7] τ is the probability that a gNB transmits at a randomly chosen slot [17].

where CW_{min} is the NR-U's minimum contention window. B_v is defined as

$$B_v = \sum_{l=v}^{\text{CW}_{\text{max}}} g_l, \tag{9}$$

where g_l is the probability that a gNB station has a backoff counter value l when the other nodes end transmissions. g_l is defined as

$$g_l = \frac{\sum_{i=0}^{m} b_{i,l+1}}{1-\sum_{i=0}^{m} b_{i,0}}, \tag{10}$$

where $b_{i,k}$ is the stationary distribution that a gNB has the backoff stage i and the backoff counter value k, and m is the maximum backoff stage in the Bianchi model. C_v is defined as

$$C_v = \sum_{l=v}^{\text{CW}_{\text{max}}} w_l, \tag{11}$$

where w_l is the probability that a gNB has a backoff counter value l after experiencing a collision. w_l is defined as

$$w_l = \frac{\sum_{i=i_s}^{m-1}\left(\frac{b_{i,0}}{2^{i+1}(\text{CW}_{\text{min}}+1)}\right)+\frac{b_{m,0}}{\text{CW}_{\text{max}}+1}}{\sum_{i=0}^{m} b_{i,0}}, \tag{12}$$

where $i_s = \max\left(\lfloor log_2 l\rfloor - log_2(\text{CW}_{\text{min}}+1), 0\right)$. δ_i is the collision resolution probability from the network perspective when the number of gNBs included in the collision is i. We define δ_i as

$$\delta_i = \sum_{x=1}^{X-1}\left[i\left(\frac{1}{X}\right)\left(\frac{x}{X}\right)^{i-1}\right], \tag{13}$$

where X is the guaranteed number of RS types. δ_i is the same as the probability that there is only one highest number when i nodes each select one number from 1 to X by allowing duplicates.

We update α_{init} as

$$\alpha_{\text{init}} = \frac{\sum_{i=2}^{n}\frac{P_i}{P_c}\delta_i}{\sum_{i=2}^{n}\frac{P_i}{P_c} i}, \tag{14}$$

where P_c is the probability that the channel is in the collision state in a slot. Updated α_{init} is equal to the number of resolved collisions divided by the number of total transmissions involved in collisions. With the updated α_{init}, we repeat the iteration. After a few iterations, we obtain converged τ, α, and bc_{min}.[8] We calculate the steady state EMS type distribution using bc_{min}. Based on [18], we obtain the steady state EMS type distribution π by solving

$$\pi\mathbf{P} = \pi, \tag{15}$$

where **P** is the transition matrix. Table 1 shows an example of **P** when the priority class is 3 and subcarrier spacing is 30 kHz.[9]

Based on the Bianchi model and [18], we define the estimated throughput of the modified Markov chain model as

$$E[S] = \frac{(P_s P_{tr} + \sum_{i=2}^{n} P_i\delta_i)E[B]}{(1-P_{tr})\sigma + P_{tr}E[T]}, \tag{16}$$

where σ is the clear channel assessment (CCA) slot duration, $E[T]$ is the average transmission duration, and $E[B]$ is the average transmitted bits in a successful transmission. In the baseline scheme, successful transmission occurs when no collision has occurred. In our scheme, however, a successful transmission can occur even if there is a collision. We reflect this difference in the numerator of (16).

We define $E[T]$ as

$$E[T] = \left(\sum_{j=1}^{13}\sum_{v=0}^{\text{CW}_{\text{max}}} \Pr(s=j)\Pr(bc_{\text{min}}=v)T(j,v)\right) + d_{\text{AIFS}}, \tag{17}$$

where $\Pr(s=j)$ is the probability that EMS type of the previous transmission is j, $\Pr(bc_{\text{min}}=v)$ is the probability that bc_{min} value is v, $T(j,v)$ is the transmission duration when EMS type of the previous transmission is j and the minimum backoff counter value is v, and d_{AIFS} is duration of AIFS.[10] We define $T(j,v)$ as

$$T(j,v) = d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v) + d_{\text{slot}}n_{\text{slot}}(j,v) + d_{\text{ems}}(j,v), \tag{18}$$

where $d_{\text{rs}}(j,v)$ is an RS duration for given j and v, $d_{\text{ims}}(j,v)$ is an initial mini-slot duration for given j and v, d_{slot} is a slot duration determined by subcarrier spacing, $n_{\text{slot}}(j,v)$ is the number of normal slots in a transmission for given j and v, and $d_{\text{ems}}(j,v)$ is an ending mini-slot duration for given j and v.

When j and v are given, we define $d_{\text{nsb}}(j,v)$ as the duration between the LBT success time and the next slot boundary. Then, we determine an initial mini-slot that has a maximum duration shorter than $d_{\text{nsb}}(j,v)$ among the 13 initial mini-slot types (including no initial mini-slot case). $d_{\text{ims}}(j,v)$ is the duration of the selected initial mini-slot. Then, $d_{\text{rs}}(j,v)$ is

$$d_{\text{rs}}(j,v) = d_{\text{nsb}}(j,v) - d_{\text{ims}}(j,v). \tag{19}$$

We define $n_{\text{slot}}(j,v)$ as

$$n_{\text{slot}}(j,v) = \left\lfloor \frac{d_{\text{mcot}} - d_{\text{rs}}(j,v) - d_{\text{ims}}(j,v)}{d_{\text{slot}}}\right\rfloor, \tag{20}$$

where d_{mcot} is the duration of MCOT. Then, we determine an ending mini-slot that has a maximum duration shorter than

[8] In Section V, we use five iterations to obtain analysis results.

[9] Each component $[a,b]$ means that EMS type i transitions to EMS type j when the bc_{min} value is between a and b.

[10] In Bianchi model, defer period is contained in a transmission slot.

$$\begin{aligned}\Pr(bc_{\text{min}}=v) = & P_s\left(S_v B_v^{n-1} - S_{v+1}B_{v+1}^{n-1}\right)\\ & + \sum_{i=2}^{n}\frac{P_i}{P_{tr}}\left[\delta_i\left(S_v C_v^{i-1}B_v^{n-i} - S_{v+1}C_{v+1}^{i-1}B_{v+1}^{n-i}\right) + (1-\delta_i)\left(C_v^i B_v^{n-i} - C_{v+1}^i B_{v+1}^{n-i}\right)\right].\end{aligned} \tag{6}$$

Table 1. Transition matrix **P** from state i to state j (priority class = 3 and subcarrier spacing = 30 kHz).

$i \backslash j$	1	2	3	4	5	6	7	8	9	10	11	12	13
1	[0,3],[51,58]	[4,7],[59,62]	[8,10],63	[11,14]	[15,18]	[19,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]
2	[43,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,15]	[16,18]	[19,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]
3	[39,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,14]	[15,18]	[19,22]	[23,26]	[27,30]	[31,34]	[35,38]
4	[35,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,14]	[15,18]	[19,22]	[23,26]	[27,30]	[31,34]
5	[31,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,15]	[16,18]	[19,22]	[23,26]	[27,30]
6	[27,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,14]	[15,18]	[19,22]	[23,26]
7	[23,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,10],63	[11,14]	[15,18]	[19,22]
8	[20,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,15]	[16,19]
9	[16,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]	[8,11],63	[12,15]
10	[12,18]	[19,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7][59,62]	[8,11],63
11	[8,15],63	[16,19]	[20,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]	[4,7],[59,62]
12	[4,11],[59,63]	[12,15]	[16,18]	[19,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]	[0,3],[55,58]
13	[0,7],[55,62]	[8,11],63	[12,14]	[15,18]	[19,22]	[23,26]	[27,30]	[31,34]	[35,38]	[39,42]	[43,46]	[47,50]	[51,54]

$d_{\text{mcot}} - d_{\text{rs}}(j,v) - d_{\text{ims}}(j,v) - d_{\text{slot}}n_{\text{slot}}(j,v)$ among the 13 ending mini-slot types (including no ending mini-slot case).

When $d_{\text{rs}}(j,v)$ is short for generating X RS types, we extend the RS duration for guaranteeing X RS types. After the RS duration is extended, $d_{\text{rs}}(j,v)$, $d_{\text{ims}}(j,v)$, and $n_{\text{slot}}(j,v)$ become $d^*_{\text{rs}}(j,v)$, $d^*_{\text{ims}}(j,v)$, and $n^*_{\text{slot}}(j,v)$, respectively. When $d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v)$ is longer than $d_{\text{SIFS}} \cdot X$, RS extension is performed in the initial mini-slot. In this case, we determine a new initial mini-slot that has a maximum duration shorter than $d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v) - (d_{\text{SIFS}} \cdot X)$ among the 13 initial mini-slot types (including no initial mini-slot case). $d^*_{\text{ims}}(j,v)$ is the duration of the new initial mini-slot. Then $d^*_{\text{rs}}(j,v)$ becomes $d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v) - d^*_{\text{ims}}(j,v)$.

On the other hand, when $d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v)$ is shorter than $d_{\text{SIFS}} \cdot X$, RS extension is performed until the first normal slot. In this case, $n^*_{\text{slot}}(j,v)$ becomes $n_{\text{slot}}(j,v) - 1$.[11] we also determine a new initial mini-slot that has a maximum duration shorter than $d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v) + d_{\text{slot}} - (d_{\text{SIFS}} \cdot X)$ among the 13 initial mini-slot types (including no initial mini-slot case). $d^*_{\text{ims}}(j,v)$ is the duration of the new initial mini-slot. Then $d^*_{\text{rs}}(j,v)$ becomes $d_{\text{rs}}(j,v) + d_{\text{ims}}(j,v) + d_{\text{slot}} - d^*_{\text{ims}}(j,v)$. With the newly defined $d^*_{\text{rs}}(j,v)$, $d^*_{\text{ims}}(j,v)$, and $n^*_{\text{slot}}(j,v)$, we can refine $T(j,v)$ as

$$T(j,v) = d^*_{\text{rs}}(j,v) + d^*_{\text{ims}}(j,v) + d_{\text{slot}}n^*_{\text{slot}}(j,v) + d_{\text{ems}}(j,v). \tag{21}$$

We define $E[B]$ as

$$E[B] = \sum_{j=1}^{13} \sum_{v=0}^{\text{CW}_{\text{max}}} \Pr(s=j)\Pr(bc_{\text{min}}=v)\,B(j,v), \tag{22}$$

where $B(j,v)$ is the transmitted information bits when EMS type of the previous transmission is j and the minimum backoff counter value is v. we define $B(j,v)$ as

$$B(j,v) = B_{\text{ims}^*} + B_{\text{slot}}n^*_{\text{slot}}(j,v) + B_{\text{ems}}, \tag{23}$$

where B_{ims^*} is the transmitted information bits at the new initial mini-slot, B_{slot} is the transmitted information bits at a normal slot, and B_{ems} is the transmitted information bits at the ending mini-slot.

B. Throughput Analysis for R-SplitC

We analyze the performance of *R-SplitC* in the NR-U only network based on [17], [18], [25]. We use the same assumptions as in the previous subsection.

[11] More than one slots can be used for RS extension. In this paper, we only consider one slot for RS extension.

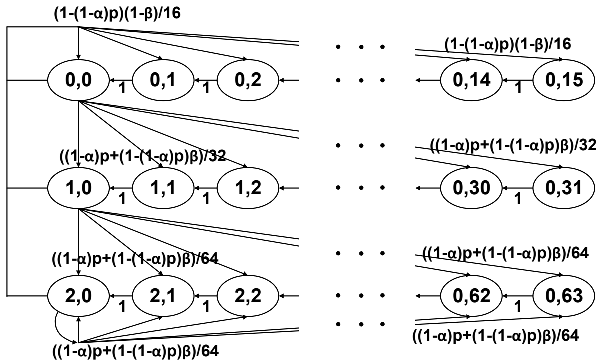

Fig. 7. An example of Markov chain model for *R-SplitC*.

Our CWS control operation additionally increases the CWS of a gNB with a specific probability when it receives an ACK. For *R-SplitC* modeling, we modify the Markov chain model of *R-Split* by expressing this probability as β, as shown in Fig. 7, when the channel access priority class is 3. If a gNB transmits a frame successfully in *R-Split*, the gNB's backoff stage becomes zero with probability $(1-(1-\alpha)p)$. In *R-SplitC*, if a gNB transmits a frame successfully, the gNB's backoff stage becomes zero with probability $(1-(1-\alpha)p)(1-\beta)$.

To get α and β, we use an iterative procedure similar to that used in the analysis of *R-Split*. First, we select α_{init} and β_{init} as input values. Then, we get τ and p through the modified Markov chain model. We obtain τ and p by solving the system of equations below.

$$\tau = \frac{2(1-2\bar{\beta}p)}{(1-2\bar{\beta}p)(W+1) + \bar{\beta}pW(1-(2\bar{\beta}p)^m)}, \tag{24}$$

$$p = 1-(1-\tau)^{n-1}, \tag{25}$$

where $\bar{\beta} = \beta_{\text{init}} + (1-\alpha_{\text{init}})(1-\beta_{\text{init}})p$ in (24). Using the results of the modified Markov chain model, we get a new bc_{min} distribution.

We define a new bc_{min} distribution of *R-SplitC* in (26), where β is the probability that the gNB increases CWS when it receives an ACK. When β is zero, (26) becomes (6).

We update α_{init} by using (14) and β_{init} as

$$\beta_{\text{init}} = \frac{\sum_{i=1}^{n-1}\binom{n-1}{i}\tau^i(1-\tau)^{n-1-i}p_i}{\sum_{i=0}^{n-1}\binom{n-1}{i}\tau^i(1-\tau)^{n-1-i}p_i}, \tag{27}$$

Table 2. Simulation parameters for an NR-U only network.

Parameter	Value
SIFS	16 μs
AIFS	43 μs
MCOT	10 ms
NR-U CW_{min}	15
NR-U CW_{max}	63
Bandwidth	20 MHz
NR-U MCS	28

where p_i is the probability that all the other i nodes select lower priorities than the gNB. We define p_i as

$$p_i = \begin{cases} \sum_{x=1}^{X-1} \left[\left(\frac{1}{X}\right) \left(\frac{x}{X}\right)^{i-1} \right], & i > 0, \\ 1, & i = 0. \end{cases} \quad (28)$$

With the updated α_{init} and β_{init}, we repeat the iteration. After a few iterations, we get converged τ, α, β, and bc_{min2}. With these converged parameters, we calculate the network throughput of *R-SplitC* using (16)–(23). The difference between *R-Split* and *R-SplitC* is that they use bc_{min} and bc_{min2} distributions, respectively.

V. PERFORMANCE EVALUATION

In this section, we validate the analysis results for our proposed schemes in an NR-U only network, and evaluate their performance in NR-U only and NR-U with Wi-Fi network environments. We implemented NR-U simulator and NR-U/Wi-Fi coexistence simulator with MATLAB. We conducted simulations in a topology where nodes are randomly distributed in a circle with a radius of 25 m. We simulated 10^6 transmissions. We implemented an ideal channel where transmission failures are caused only by collisions and used fixed MCS for the NR-U only network to compare with the analysis result. We implemented the 3GPP urban micro (UMi) path loss model and adaptive modulation and coding scheme (AMC) for the NR-U/Wi-Fi network for more realistic environment. We set the maximum MCOT and A-MPDU duration in the standard. Other detailed simulation parameters are summarized in Tables 2 and 3.

For performance comparison, we consider two schemes: 1) The baseline operation of NR-U, which uses RS only for channel reservation and 2) CR-LBT, which transmits an RS probabilistically in each CR-slot for collision resolution [15].

A. Performance Evaluation for an NR-U only Network

Fig. 8 shows the network throughput of *R-Split*. The number after *R-Split* means the number of RS types guaranteed through RS extension. The gap between simulation and analysis results of *R-Split* is merely 0.04% on average. In the baseline, network throughput greatly decreases as the number of contending nodes increases. This is because the damage caused by the increasing collision is getting bigger. CR-LBT shows almost similar performance to the baseline. This is because the RS duration in NR-U is too short to obtain collision resolution performance. *R-Split* shows the best performance when the number of guaranteed RS types is 10. If the number of guaranteed RS types is too small, the performance of collision resolution is poor. On the contrary, if the number of RS types is too large, the overhead due to the reduction of the data slot is greater than the increase of the collision resolution performance. Therefore, using an appropriate number of RS types shows the best results. Compared to the baseline scheme and CR-LBT, *R-Split* 10 shows the throughput gain of 30.86% and 30.66% when the number of contending nodes is 10, respectively.

Fig. 9 shows the network throughput of *R-SplitC*. The difference between simulation and analysis results is merely 0.05% on average. The overall trend of *R-SplitC* is the same as that of *R-Split*. When the number of guaranteed RS types is 10, the performance of R-SplitC is the best. The performance of *R-SplitC* is slightly higher than that of *R-Split*. This is because the additional CWS increase of *R-SplitC* shows an effect of collision reduction. Compared to the baseline scheme and CR-LBT, *R-SplitC* 10 shows the throughput gain of 31.64% and 31.44% when the number of contending nodes is 10, respectively.

Fig. 10 shows the collision time ratio according to the number of contending nodes. In the baseline scheme, the collision time ratio increases with the number of contending nodes. CR-LBT shows similar collision time ratio compared to the baseline scheme due to short RS duration. In contrast, the collision time ratios in our schemes are considerably lower than that in the baseline scheme and CR-LBT, and do not increase significantly even when the number of contending nodes increases. Our schemes successfully avoid collisions by using the new RS structure. *R-SplitC* 10 has a slightly lower collision time ratio than *R-Split* 10. This is due to the fact that the collision resolution is resolved through *R-Split* operation, but the CWS increase occurs so little that the collision itself increases. *R-SplitC* has a lower collision time ratio because it does not increase collision by calibrating it through the CWS control operation and also takes the collision resolution effect.

B. Performance Evaluation for an NR-U/Wi-Fi Network.

We evaluate the performance of our proposed schemes under the coexistence of NR-U and Wi-Fi, where NR-U gNBs and Wi-Fi APs coexist in a one-to-one ratio. Fig. 11 shows NR-U throughput, Wi-Fi throughput, and sum throughput according to the number of contending nodes when subcarrier spacing is 30 kHz. Wi-Fi APs do not use RTS/CTS. With the num-

$$\begin{aligned} \Pr\left(bc_{\text{min2}} = v\right) = & P_s\left(1-\beta\right)\left(S_v B_v^{n-1} - S_{v+1} B_{v+1}^{n-1}\right) + P_s\beta\left(C_v B_v^{n-1} - C_{v+1} B_{v+1}^{n-1}\right) \\ & + \sum_{i=2}^{n} \frac{P_i}{P_{tr}} \left[\delta_i\left(1-\beta\right)\left(S_v C_v^{i-1} B_v^{n-i} - S_{v+1} C_{v+1}^{i-1} B_{v+1}^{n-i}\right)\right. \\ & \left. + \delta_i\beta\left(C_v^i B_v^{n-i} - C_{v+1}^i B_{v+1}^{n-i}\right) + \left(1-\delta_i\right)\left(C_v^i B_v^{n-i} - C_{v+1}^i B_{v+1}^{n-i}\right)\right]. \end{aligned} \quad (26)$$

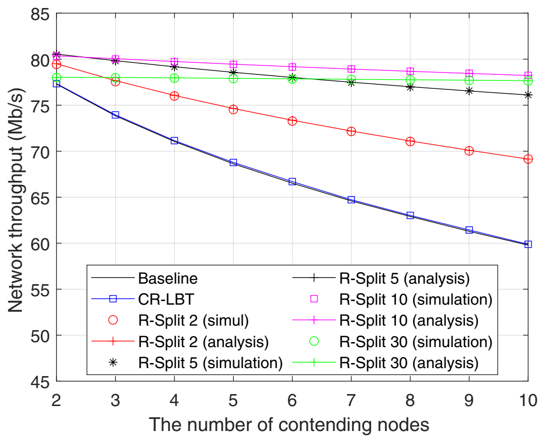

Fig. 8. Network throughput of *R-Split*.

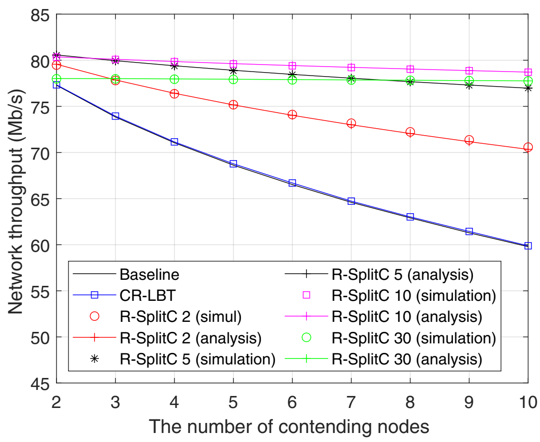

Fig. 9. Network throughput of *R-SplitC*.

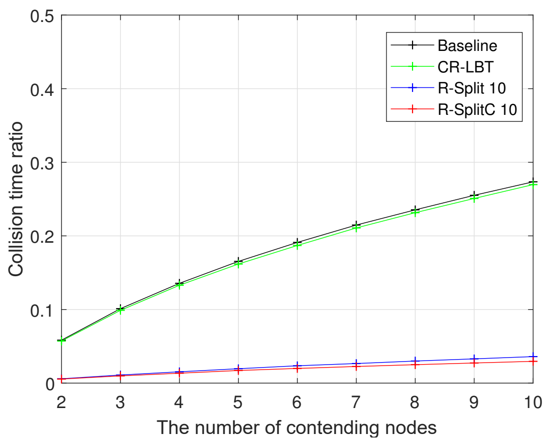

Fig. 10. Collision time ratio.

ber of nodes in the baseline scheme, the throughput of NR-U and Wi-Fi decrease due to increased collisions. In CR-LBT, NR-U slightly decreases and Wi-Fi slightly increases compared with the baseline scheme. This is because the operation for Wi-Fi of the CR-LBT sometimes operates. In *R-SplitC* 10, NR-U throughput is much larger than in the baseline scheme

Table 3. Simulation parameters for an NR-U/Wi-Fi network.

Parameter	Value
SIFS	16 μs
AIFS	43 μs
MCOT	8 ms
NR-U CW_{min}	15
NR-U CW_{max}	63
A-MPDU duration	5.484 ms
Wi-Fi CW_{min}	15
Wi-Fi CW_{max}	1023
Bandwidth	20 MHz
Wi-Fi PHY	802.11ac, SISO
Wi-Fi rate adaptation	Minstrel VHT
NR-U rate adaptation	AMC

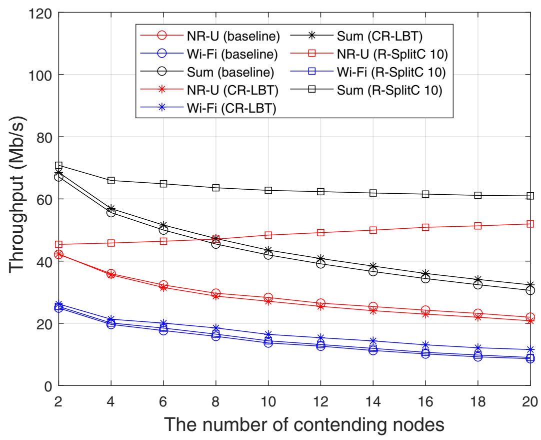

Fig. 11. Performance of NR-U and Wi-Fi without RTS/CTS (30 kHz subcarrier spacing).

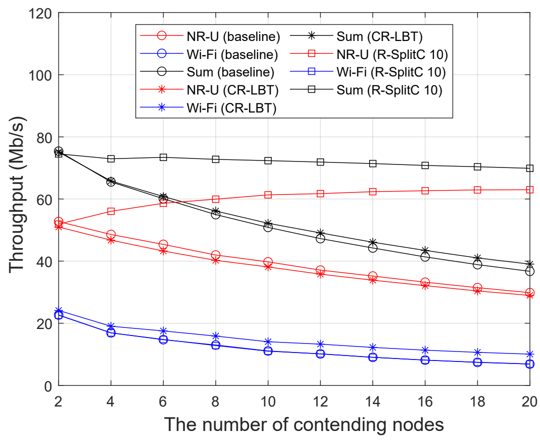

Fig. 12. Performance of NR-U and Wi-Fi with RTS/CTS (30 kHz subcarrier spacing).

and CR-LBT.

There are two reasons for the NR-U throughput improvement in *R-SplitC* 10. First, *R-SplitC* 10 resolves collisions of NR-U transmissions successfully. Second, due to the collision resolution, MCS underestimation, which occurs each time a collision occurs, occurs less frequently. Thus, the average MCS in our proposed schemes is greater than that in the baseline scheme. *R-SplitC* 10 tries to keep the CWS value of NR-U similar to the baseline scheme, and accordingly, it boosts NR-U

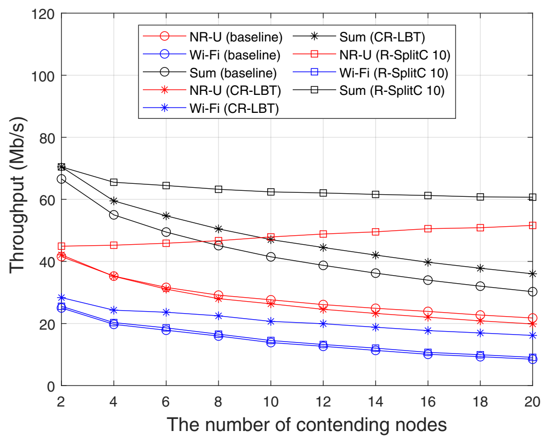

Fig. 13. Performance of NR-U and Wi-Fi without RTS/CTS (15 kHz subcarrier spacing).

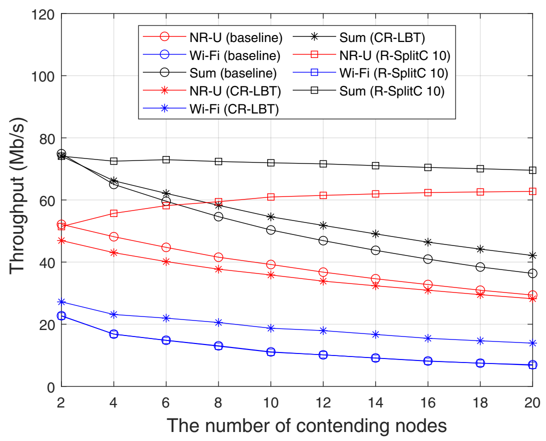

Fig. 14. Performance of NR-U and Wi-Fi with RTS/CTS (15 kHz subcarrier spacing).

performance without sacrificing Wi-Fi performance. When the number of contending nodes is 20, *R-SplitC* 10 increases the NR-U throughput by 136.6% and also increases the Wi-Fi throughput by 4.44% compared to the baseline scheme. As a result, *R-SplitC* 10 increases the overall network throughput by 99.29%.

We evaluate the performance under the coexistence of NR-U and Wi-Fi using RTS/CTS. Fig. 12 shows NR-U throughput, Wi-Fi throughput, and sum throughput according to the number of contending nodes when subcarrier spacing is 30 kHz. Compared to the no RTS/CTS case, the throughput gap between NR-U and Wi-Fi becomes larger. This is because when NR-U and Wi-Fi transmissions collide, Wi-Fi transmission stops first due to the decoding failure of RTS frame while NR-U transmission continues. In CR-LBT, NR-U slightly decreases and Wi-Fi slightly increases compared with the baseline scheme as in the no RTS/CTS case. *R-SplitC* 10 increases the throughput of NR-U compared to the baseline scheme. It also maintains almost the same Wi-Fi performance as the baseline scheme. When the number of contending nodes is 20, *R-SplitC* 10 increases the throughput of NR-U by 111% and also increases the throughput of Wi-Fi by 0.34% compared to the baseline scheme. *R-SplitC* 10 improves the overall network throughput by 90.3% compared to the baseline.

We evaluate the coexistence performance of NR-U and Wi-Fi in 15 kHz subcarrier spacing environment. As the subcarrier spacing is changed from 30 kHz to 15 kHz, the slot duration increases from 0.5 ms to 1 ms, and the OFDM symbol duration also doubles. That is, the RS duration is also doubled. Fig. 13 shows NR-U throughput, Wi-Fi throughput, and sum throughput according to the number of contending nodes when subcarrier spacing is 15 kHz. Wi-Fi APs do not use RTS/CTS. In the baseline scheme, NR-U and Wi-Fi show almost similar performance to 30 kHz subcarrier spacing case. In CR-LBT, Wi-Fi increases compared to 30 kHz subcarrier spacing thanks to increased RS duration. *R-SplitC* 10 shows similar results compared with 30 kHz subcarrier spacing. It is because that *R-SplitC* 10 has similar RS duration regardless of subcarrier spacing. When the number of contending nodes is 20, *R-SplitC* 10 increases the throughput of NR-U by 137.1% and also increases the throughput of Wi-Fi by 7.1% compared to the baseline scheme.

Fig. 14 shows NR-U throughput, Wi-Fi throughput, and sum throughput according to the number of contending nodes when subcarrier spacing is 15 kHz. Wi-Fi APs use RTS/CTS. In the baseline scheme, NR-U and Wi-Fi show almost similar performance to 30 kHz subcarrier spacing case. In CR-LBT, Wi-Fi increases compared to 30 kHz subcarrier spacing thanks to increased RS duration. *R-SplitC* 10 shows similar results compared with 30 kHz subcarrier spacing. When the number of contending nodes is 20, *R-SplitC* 10 increases the throughput of NR-U by 113.6% and also decreases the throughput of Wi-Fi by 2.6% compared to the baseline scheme.

VI. CONCLUSION

In this paper, we focused on the collision problem that occurs when multiple NR-U gNBs are transmitting at the same time. To solve this problem, we proposed a collision resolution scheme, termed *R-Split*, that aims to minimize the collision probability by introducing a new RS structure. *R-Split* extends RS duration and uses a split RS, and place an idle gap of SIFS duration between front and rear RSs to sense the channel in the middle of RS transmissions. Even when an RS collision occurs, *R-Split* enables an NR-U gNB to make a successful transmission. We added a CWS control procedure to *R-Split* to compensate for CWS reduced by *R-Split* and named it as *R-SplitC*, which protects Wi-Fi traffic when NR-U and Wi-Fi traffic coexist. *R-SplitC* allows a gNB winning the contention to increase its CWS probabilistically to provide room for Wi-Fi transmission. Through mathematical analysis and simulation, we confirmed that *R-SplitC* significantly improves the performance of NR-U without sacrificing Wi-Fi performance.

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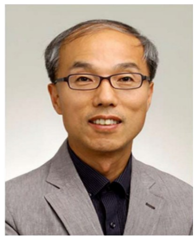

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