Could IEEE 802.11bc Enhance Data Broadcast Performance for Moving Station: A Frame Loss Perspective

Leiyu Que[†], Honghao Ju[†*], Xuming Fang[†], Yan Long[†], Rong He[†], and Lei Huang[‡]
[†]Key Laboratory of Information Coding and Transmission, Southwest Jiaotong University, Chengdu, China
[‡]OPPO Research Institute, Singapore

2022 IEEE 95th Vehicular Technology Conference (VTC2022-Spring) | 978-1-6654-8243-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/VTC2022-Spring54318.2022.9860960

***Abstract*—IEEE 802.11bc is especially designed for enhancing the broadcast performance in wireless local network. Focusing on improving the broadcast data frame scheduling and origin authenticity performance, the broadcast data frame scheduling scheme is completely re-designed and the data origin authenticity is introduced in the IEEE 802.11bc. However, after introducing these updated mechanisms, the data broadcast performance due to station mobility, especially during the handover period, remains un-explored. Motivated by this, in this paper, we investigate the downlink handover broadcast data frame loss rate in the IEEE 802.11bc. With special focus on the updated broadcast data frame scheduling and data authentication in the IEEE 802.11bc, we derive an analytical model for the downlink broadcast frame loss rate. Based on the analytical model and simulation test, we give the broadcast parameters configuration for the specified average broadcast data frame loss rate constraint.**

***Index Terms*—IEEE 802.11bc, broadcast frame loss rate, authentication, handover**

I. Introduction

Owing to the low cost and easy deployment, wireless local network (WLAN) has been becoming more and more popular in the past years. Particularly, as its market expands, applying the WLAN for data broadcast (e.g., intelligent transportation broadcast, stadium video distribution) has promising future. However, the current WLAN does not support broadcast well. Specifically, for the broadcast data frame scheduling, the distributed coordinated function (DCF) is adopted, which cannot provide broadcast time guarantee. Moreover, it does not provide mechanism for the broadcast data frame authentication, and this is critical for the broadcast since it can avoid fake data injection.

To improve the broadcast data frame scheduling and to provide data frame origin authentication, IEEE 802.11bc project was established in 2018, aiming to provide enhanced broadcast service (EBCS) in WLAN. According to the current completed draft [1], to improve the downlink (DL) EBCS, IEEE 802.11bc introduces the EBCS Info frame, which centrally controls the DL EBCS data frame scheduling. Through this, IEEE 802.11bc can provide a time guarantee for the DL EBCS data frame broadcast. Moreover, IEEE 802.11bc introduces hash chain frame authentication (HCFA) without instant authentication for authenticating the EBCS data frame, such that the fake data injection can be avoided.

The above technique in the IEEE 802.11bc can enhance the DL broadcast performance for the stationary station (STA). However, after introducing these updated mechanisms, the data broadcast performance due to STA mobility, especially during the handover period, remains un-explored. Such performance investigation is critical for evaluating whether the IEEE 802.11bc can be applied to data broadcast in the mobile scenario.

Motivated by the above, in this paper, we study the DL EBCS data frame loss rate during the handover period in the IEEE 802.11bc. Our main contributions are as follows:

- We specifically investigate the DL EBCS data frame loss rate during the handover period in the IEEE 802.11bc, where the central EBCS data frame scheduling and the EBCS data frame authentication are considered. Especially for the EBCS data frame authentication, even if the frame can be received successfully, it is still considered as frame loss if the frame cannot be authenticated;
- Within the IEEE 802.11bc framework, we study the DL EBCS data frame loss rate versus EBCS Info frame transmission interval, EBCS data frame transmission interval, authentication key period, handover delay and clock offset between adjacent AP's. These broadcast parameters are unique in the IEEE 802.11bc;
- We derive an analytical model for the average EBCS data frame loss rate due to handover, and give the broadcast parameters configuration for the specified average EBCS data frame loss rate constraint.

II. Literature Review

For the broadcast performance analysis due to handover, the literature can be categorized as: handover trigger time selection, handover latency reduction, and the handover frame loss rate decreasing. Macha *et al.* [2], Pahlavan *et al.* [3], Song *et al.* [4] and Ali *et al.* [5] investigate the handover decision algorithm for determining the handover trigger time; Chang *et al.* [6], Mishra *et al.* [7], Sangheon *et al.* [8] and Mishra *et al.* [9] study the mechanism for reducing handover latency; Ali *et al.* [10], [11] and Stevens-Navarro *et al.* [12] investigate the scheme for decreasing the data frame loss rate

*Corresponding author (Honghao Ju: hhju@swjtu.edu.cn)

due to handover. However, these works cannot be applied to the handover performance analysis in the IEEE 802.11bc. This is because that IEEE 802.11bc introduces central EBCS data frame scheduling and EBCS data frame authentication, which are not considered in the above literature. Especially for the EBCS data frame authentication, even if the frame can be received successfully, it is still considered as frame loss if the frame cannot be authenticated, and this is not discussed in the existing literature.

III. DL EBCS Data Frame Reception and Handover in the IEEE 802.11bc

In this section, we overview the DL EBCS data frame reception procedure under HCFA without instant authentication scheme and the handover procedure for the DL EBCS in the IEEE 802.11bc.

A. EBCS Data Frame Reception for HCFA Without Instant Authentication

To provide data frame origin authenticity, IEEE 802.11bc provides HCFA without instant authentication method. It has two types of keys: HCFA base key and HCFA authentication key. The authentication key is generated from the base key, and is for authenticating the EBCS data frame. We denote the HCFA key period as T_K, in which the base key and authentication key remain unchanged. The EBCS Info frame is broadcast periodically. The EBCS data frame is broadcast during the EBCS Info frame transmission interval, and the broadcast time is scheduled by the EBCS Info frame.

To avoid data frame forgery, in the HCFA without instant authentication method, the authentication key is published after the EBCS data frame, which is two T_K in the IEEE 802.11bc. Thus, the STA has to buffer the EBCS data frame before authenticating. Taking the HCFA base key number as 9 for example in Fig. 1, we describe the EBCS data frame reception procedure for HCFA without instant authentication as follows:

- The STA receives and authenticates the EBCS Info frame to make sure the HCFA base key $B_{s,8}$ is trustworthy;
- In the key period 0, after receiving the EBCS data frame, the STA can obtain the base key $B_{s,7}$. The base key $B_{s,7}$ can be verified by checking whether hash$\{B_{s,7}\}$ is equal to $B_{s,8}$;
- In the key period $i, i = 1, \cdots, 5$, the corresponding base key $B_{s,m}, m = 6, \cdots, 2$ can be verified. These base keys can be used for verifying the authentication key $A_{s,m}, m = 5, \cdots, 2$. Once the authentication key is verified, the corresponding broadcast data $m = 5, \cdots, 2$ can be authenticated;
- For the broadcast data $m = 1, 0$, they can be authenticated by base keys $B_{s,m}, m = 1, 0$, which are contained in the next EBCS Info frame;
- If the broadcast data cannot be authenticated, they should be discarded.

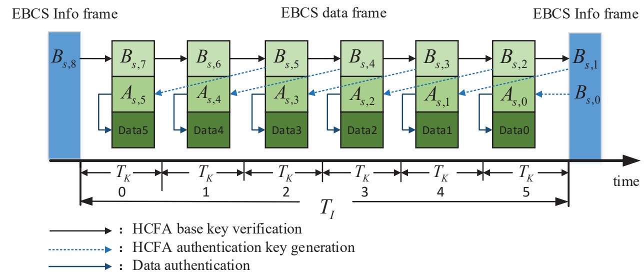

Fig. 1. EBCS Data Frame Reception

B. DL EBCS Handover Procedure

For the handover in the IEEE 802.11bc, as in Fig. 2, the current AP and target AP are both connected to the same broadcast server, and use the same seed sequence to produce the base key. If the STA hands over from the current AP to the target AP, a re-connection with the target AP is required [1]. Thus, besides EBCS Info frame transmission interval, EBCS data frame transmission interval, and HCFA key period, the handover delay should be considered for the DL EBCS data frame loss rate analysis. Moreover, for the current AP and the target AP, they may be unsynchronized, and their clock offset should also be incorporated in evaluating the DL EBCS data frame loss rate.

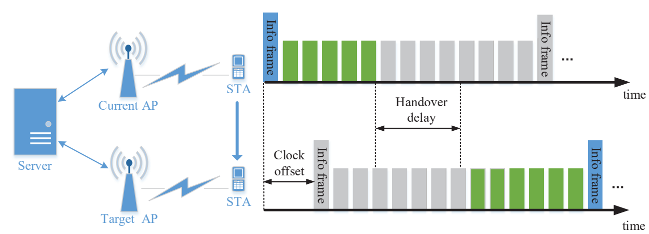

Fig. 2. DL EBCS Handover

IV. DL EBCS Data Frame Loss Rate Analysis

In this section, we provide an analytical model for investigating the DL EBCS data frame loss rate due to handover for the IEEE 802.11bc.

A. EBCS Data Frame Loss Rate Model

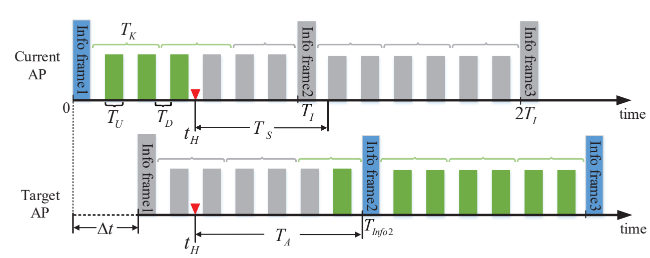

Fig. 3. EBCS Data Frame Loss Rate Model

As in Fig. 3, for the current AP and the target AP, we assume that their clock offset is Δt, where $\Delta t \geq 0$ if the time clock of target AP is delayed with the current AP, and otherwise $\Delta t < 0$. We denote the EBCS Info frame transmission interval as T_I, and denote the handover delay as T_S, which typically is 300ms [13]. We suppose that the EBCS data frame is periodically broadcast within T_I. The repetition interval is T_D and the time duration for each broadcast is T_U. Since the EBCS Info frame transmission interval is relatively large, which is in the scale of multiple beacon intervals, we assume that the handover delay is smaller than two EBCS Info frame transmission intervals. Thus, we only consider the EBCS data frame loss rate within two EBCS Info frame intervals during the handover period. However, our analysis can also extend to covering more EBCS Info frame intervals.

We denote the number of EBCS data frames within two Info intervals as N_D, which can be written as

$$N_D = \frac{2(T_I - T_D)}{T_D + T_U}. \quad (1)$$

We write the broadcast time of EBCS Info frame 1 in the current AP as 0, and the EBCS Info frame 2 broadcast time in the target AP as T_{Info2}. Considering the clock offset, we have

$$T_{\text{Info2}} = \Delta t + T_I. \quad (2)$$

We denote the handover trigger time as t_H. Since the handover trigger time depends on the STA mobility, and we assume that t_H is uniformly distributed in $[0, T_I]$. The time from t_H to T_{Info2} is denoted as T_A, which satisfies

$$T_A = T_{\text{Info2}} - t_H. \quad (3)$$

Given the above, according to whether the STA can receive the EBCS Info frame 2 from the target AP after handover, we divide our analysis into two cases, and investigate the EBCS data frame loss rate and the occurrence probability for each case separately.

B. EBCS Info Frame 2 From Target AP Can Be Received

In this case, the moving STA can receive the EBCS Info frame 2 from the target AP after handover, which indicates $T_S \leq T_A$.

For the EBCS data frame loss rate analysis, as in Fig. 4 and Fig. 1, since the Info frame 2 can be received, the base key $B_{s,m}, m = 1, 0$ can be obtained. Using the hash operation, the other base key $B_{s,m}$ can be obtained. Since the target AP and current AP use the same key sequence, the base key $B_{s,m}$ could be further used for verify the authentication key of the cached EBCS data frames from the current AP. Therefore, the cached EBCS data frames before handover from the current AP can be authenticated. Also, the cached EBCS data frames from the target AP after handover can also be authenticated by using the base keys provided in the EBCS Info frame 2 and EBCS Info frame 3.

Therefore, if the EBCS Info frame 2 can be received, the frame loss is from the missing frames due to handover. Considering the clock offset between adjacent AP's, the missing

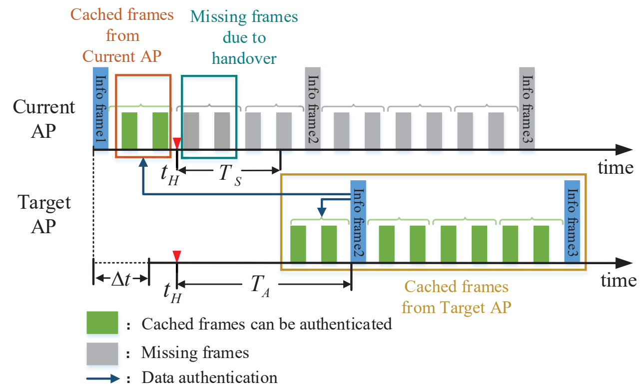

Fig. 4. EBCS Data Frame Loss Analysis in Case 1

frame number L_1 during the handover can be written as

$$L_1 = \frac{T_S - \Delta t}{T_D + T_U}. \quad (4)$$

Given the above, the EBCS data frame loss rate in this case P_{loss1} can be written as

$$P_{\text{loss1}} = \frac{L_1}{N_D} = \frac{T_S - \Delta t}{2(T_I - T_D)}. \quad (5)$$

The EBCS data frame loss rate (5) shows that it is independent of handover trigger time t_H. Therefore, the average EBCS data frame loss rate in this case $\bar{P}_{\text{loss1}}$ can be written as

$$\bar{P}_{\text{loss1}} = P_{\text{loss1}}. \quad (6)$$

For the occurrence probability analysis in this case, considering the constraint $T_S \leq T_A$ and using (2) and (3), we can derive

$$t_H \leq T_I - T_S + \Delta t. \quad (7)$$

Given the uniform distribution of t_H, we can derive the occurrence probability in this case P_{occur1} as

$$P_{\text{occur1}} = \frac{T_I - T_S + \Delta t}{T_I}. \quad (8)$$

C. EBCS Info frame 2 From Target AP Cannot Be Received

In this case, the moving STA cannot receive the EBCS Info frame 2 from target AP after handover, which indicates $T_S > T_A$.

For the EBCS data frame loss rate in this case, since the base key in the EBCS Info frame 2 cannot be obtained, the cached EBCS data frames from the current AP cannot be entirely authenticated. The authenticated EBCS data frame portion is determined by the number of HCFA key period before the handover trigger time. We will investigate this by focusing on $t_H \leq 2T_K$ and $t_H > 2T_K$ separately.

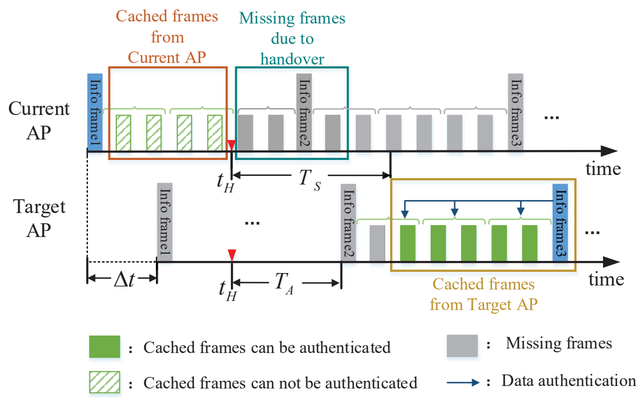

Fig. 5. EBCS Data Frame Loss Analysis if $t_H \leq 2T_K$

1) $t_H \leq 2T_K$: If the handover trigger time $t_H \leq 2T_K$, as in Fig. 5, since there are no base key provided for authentication, all the cached EBCS data frames from the current AP cannot be authenticated.

For the cached frames from target AP after handover, they can be authenticated by using the base key provided in Info frame 3.

Thus, if $t_H \leq 2T_K$, the frame loss is from the cached frames from the current AP before handover and the missing frames during handover period. The frame loss number L_{2_1} can be written as

$$L_{2\_1} = \frac{t_H}{T_D + T_U} + \frac{T_S - \Delta t - T_D}{T_D + T_U}. \tag{9}$$

Thus, the EBCS data frame loss rate in this case $P_{\text{loss2\_1}}$ can be written as

$$P_{\text{loss2\_1}} = \frac{L_{2\_1}}{N_D} = \frac{t_H + T_S - \Delta t - T_D}{2(T_I - T_D)}. \tag{10}$$

Given (10), since t_H is uniformly distributed in $[0, T_I]$, the average EBCS data frame loss rate $\bar{P}_{\text{loss2\_1}}$ is

$$\bar{P}_{\text{loss2\_1}} = \frac{0.5T_I + T_S - \Delta t - T_D}{2(T_I - T_D)}. \tag{11}$$

For the occurrence probability analysis, we have to ensure $t_H \leq 2T_K$ and $T_S > T_A$, using (2) and (3), we have

$$t_H > T_I - T_S + \Delta t, \tag{12}$$

$$t_H \leq 2T_K. \tag{13}$$

Since the occurrence probability depends on the relation between $T_I - T_S + \Delta t$ and $2T_K$, to simplify the notation, we denote

$$A = T_I - T_S + \Delta t,$$
$$B = 2T_K.$$

Given the uniform distribution of t_H, the occurrence probability $P_{\text{occur2\_1}}$ is the joint probability of (12) and (13), and can be derived as follows:

$$\text{If } A \leq B : P_{\text{occur2\_1}} = \frac{2T_K - T_I + T_S - \Delta t}{T_I}, \tag{14}$$

$$\text{Else if } A > B : P_{\text{occur2\_1}} = 0. \tag{15}$$

2) $t_H > 2T_K$: If the handover trigger time $t_H > 2T_K$, as in Fig. 6, part of the cached EBCS data frames from the current AP before handover can be authenticated, and the portion is determined by the number of HCFA key periods K before the handover trigger time, and we can write K as

$$K = \lceil \frac{t_H}{T_K} \rceil, \tag{16}$$

where $x \leq \lceil x \rceil < x + 1$.

In the IEEE 802.11bc, the HCFA base key is published two T_K later to the corresponding EBCS data frame as in Fig. 1, thus, if $t_H > 2T_K$, the cached EBCS data frames from the current AP within the period $[0, (K-2)T_K]$ can be authenticated, and the cached EBCS data frames from the current AP within the period $[(K-2)T_K, t_H]$ cannot be authenticated and should be discarded.

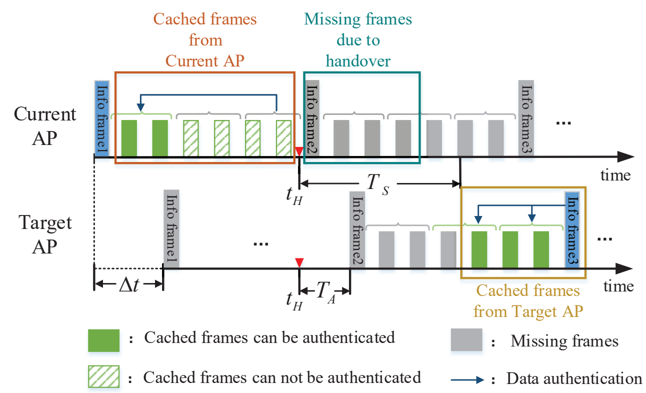

Fig. 6. EBCS Data Frame Loss Analysis if $t_H > 2T_K$

Thus, if $t_H > 2T_K$, the frame loss is from the cached frames from the current AP before handover and the missing frames during handover period. The frame loss number $\hat{L}_{2\_2}$ can be written as

$$\hat{L}_{2\_2} = \lceil \frac{t_H - (K-2)T_K}{T_D + T_U} \rceil + \frac{T_S - \Delta t - T_D}{T_D + T_U}. \tag{17}$$

Since $x \leq \lceil x \rceil < x + 1$, using (16), the worst frame loss number L_{2_2} can be written as

$$L_{2\_2} = \frac{2T_K + T_D + T_U - \Delta t + T_S}{T_D + T_U}. \tag{18}$$

Thus, if $t_H > 2T_K$, the EBCS data frame loss rate $P_{\text{loss2\_2}}$ can be written as

$$P_{\text{loss2\_2}} = \frac{L_{2\_2}}{N_D} = \frac{2T_K + T_D + T_U + T_S - \Delta t}{2(T_I - T_D)}. \tag{19}$$

Since $P_{\text{loss2\_2}}$ is independent of handover trigger time t_H, the average EBCS data frame loss rate $\bar{P}_{\text{loss2\_2}}$ can be written as

$$\bar{P}_{\text{loss2\_2}} = P_{\text{loss2\_2}}. \tag{20}$$

For the occurrence probability analysis, we have to ensure $t_H > 2T_K$ and $T_S > T_A$, using (2) and (3), we have

$$t_H > T_I - T_S + \Delta t, \tag{21}$$

$$t_H > 2T_K. \quad (22)$$

Using similar analysis as in $t_H \leq 2T_K$, the occurrence probability $P_{\text{occur2\_2}}$ can be derived as follows:

$$\text{If } A \leq B : P_{\text{occur2\_2}} = \frac{T_I - 2T_K}{T_I}, \quad (23)$$

$$\text{Else if } A > B : P_{\text{occur2\_2}} = \frac{T_S - \Delta t}{T_I}. \quad (24)$$

D. Average EBCS Data Frame Loss Rate

Given the above, the average EBCS data frame loss rate can be written as

$$\bar{P}_{\text{loss}} = \bar{P}_{\text{loss1}} \cdot P_{\text{occur1}} + \bar{P}_{\text{loss2\_1}} \cdot P_{\text{occur2\_1}} + \bar{P}_{\text{loss2\_2}} \cdot P_{\text{occur2\_2}}.$$

Depending on A and B, we can derive $\bar{P}_{\text{loss}}$ as in the following:

- $A \leq B$: Substituting $\bar{P}_{\text{loss1}}$, P_{occur1}, $\bar{P}_{\text{loss2\_1}}$, $P_{\text{occur2\_1}}$, $\bar{P}_{\text{loss2\_2}}$, and $P_{\text{occur2\_2}}$ with (5), (8), (11), (14), (19), and (23), we have

$$\bar{P}_{\text{loss}} = \frac{-0.5T_I + 3T_K + 1.5T_S - 1.5\Delta t + 2T_D + T_U}{2(T_I - T_D)} - \frac{4{T_K}^2 - 2T_K T_U + T_D(\Delta t - T_S - 4T_K)}{2(T_I - T_D)T_I}. \quad (25)$$

- $A > B$: Substituting $\bar{P}_{\text{loss1}}$, P_{occur1}, $\bar{P}_{\text{loss2\_1}}$, $P_{\text{occur2\_1}}$, $\bar{P}_{\text{loss2\_2}}$, and $P_{\text{occur2\_2}}$ with (5), (8), (11), (15), (19), and (24), we have

$$\bar{P}_{\text{loss}} = \frac{(T_S - \Delta t)(T_I + 2T_K + T_D + T_U)}{2(T_I - T_D)T_I}. \quad (26)$$

V. Performance Evaluation

We evaluate the average EBCS data frame loss rate in this section. We set the handover delay $T_S = 300$ms [13], the time duration for each broadcast $T_U = 10$ms. We testify the average EBCS data frame loss rate versus EBCS Info frame transmission interval T_I, EBCS data frame transmission interval T_D, HCFA key period T_K, and clock offset Δt.

We first study the average EBCS data frame loss rate versus T_D and T_I, by setting $\Delta t = 50$ms and $T_K = 100$ms. Since IEEE 802.11bc specify the EBCS Info frame transmission interval as multiple beacon intervals, which typically is 100ms, we set $T_I = 100n$(ms), where n is a positive integer. We show the average EBCS data frame loss rate versus T_I given a specified T_D in Fig. 7. We could observe that the average EBCS data frame loss rate decreases as T_D decreases. However, when $T_I \geq 800$ms, the marginal gain from configuring T_D becomes smaller, and the average EBCS data frame loss rate is mainly determined by T_I.

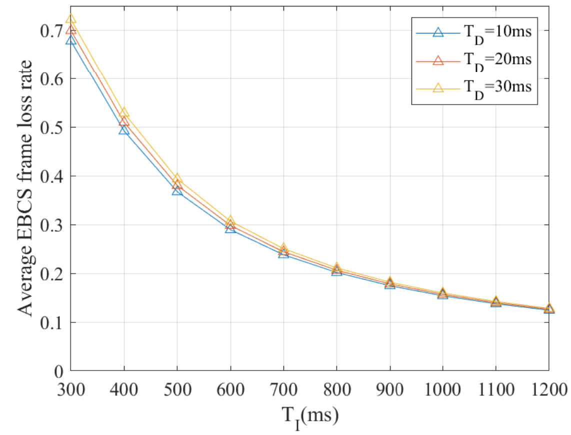

Fig. 7. Average EBCS Data Frame Loss Rate Versus T_D and T_I

We then investigate the average EBCS data frame loss rate versus T_K and T_I, by setting $\Delta t = 50$ms and $T_D = 10$ms in Fig. 8. We could observe that the average EBCS data frame loss rate decreases as T_K decreases. However, when $T_I \geq 1200$ms, the marginal gain from configuring T_K becomes smaller, and the average EBCS data frame loss rate is mainly determined by T_I.

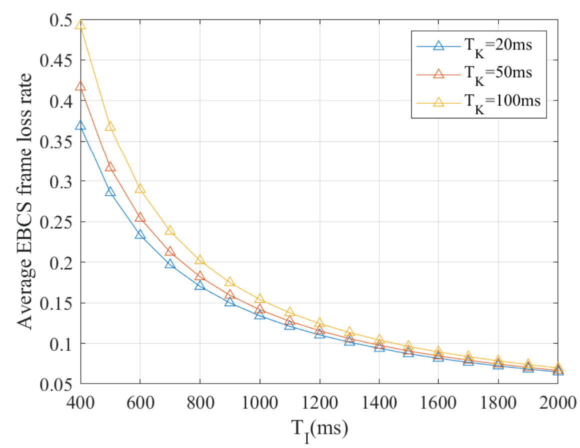

Fig. 8. Average EBCS Data Frame Loss Rate Versus T_K and T_I

We also investigate the average EBCS data frame loss rate versus Δt and T_I, by setting $T_D = 10$ms and $T_K = 50$ms in Fig. 9. We could observe that the average EBCS data frame loss rate increases as Δt decreases. However, when $T_I \geq 1200$ms, Δt can still have a dominant impact on the average EBCS data frame loss rate.

Based on the above simulation results, in Tab. I, we give the broadcast parameters configuration for the specified average EBCS data frame loss rate constraint.

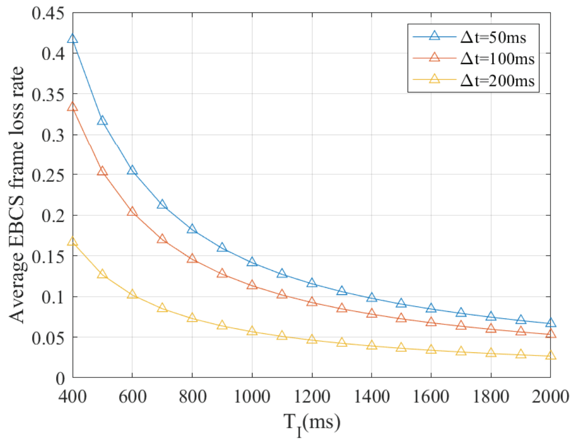

Fig. 9. Average EBCS Data Frame Loss Rate Versus Δt and T_I

TABLE I
BROADCAST PARAMETERS CONFIGURATION

Average Frame Loss Rate	T_I(ms)	T_D(ms)	T_K(ms)	Δt(ms)
5%	1300	10	50	200
10%	1100	10	50	100
15%	800	10	50	100
20%	800	10	100	50
25%	700	20	100	50
30%	600	20	100	50

VI. CONCLUSION

Focusing on the updated broadcast data frame scheduling and data origin authentication mechanism in the IEEE 802.11bc, we analyze the average EBCS data frame loss rate due to handover. We specifically investigate the average EBCS data frame loss rate versus EBCS Info frame transmission interval, EBCS data frame transmission interval, HCFA key period, handover delay, and clock offset. We derive an analytical model for the broadcast frame loss rate with respect to the above parameters. Through simulation, we give the broadcast parameters configuration for the specified average EBCS data frame loss rate constraint.

ACKNOWLEDGEMENT

This work is supported in part by OPPO R&D Fund, NSFC under Grant 61601380, NSFC under Grant 62071393, NSFC High-Speed Rail Joint Foundation under Grant U1834210, and Sichuan Science and Technology Program under Grant 2022NSFSC0912, 2020YJ0218, 2022YFG0170, and 2021YFQ0056.

REFERENCES

[1] *IEEE P802.11-TGbc/D1.05, Draft Standard for Information Technology - Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks - Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 5: Enhanced Broadcast Services*, IEEE Std. 802.11, 2021.

[2] P. Macha and J. Wozniak, "Performance Evaluation of IEEE 802.11 Fast BSS Transition Algorithms," in *Proc. WMNC*, 2010, pp. 1–5.

[3] K. Pahlavan, P. Krishnamurthy, A. Hatami, M. Ylianttila, J. Makela, R. Pichna, and J. Vallstron, "Handoff in Hybrid Mobile Data Networks," *IEEE Personal Communications*, vol. 7, no. 2, pp. 34–47, 2000.

[4] Y. Song, P. Kong, and Y. Han, "Power-Optimized Vertical Handover Scheme for Heterogeneous Wireless Networks," *IEEE Communications Letters*, vol. 18, no. 2, pp. 277–280, 2014.

[5] T. M. Ali and M. Saquib, "Analytical Framework for WLAN-Cellular Voice Handover Evaluation," *IEEE Transactions on Mobile Computing*, vol. 12, no. 3, pp. 447–460, 2013.

[6] B. Chang and J. Chen, "Cross-Layer-Based Adaptive Vertical Handoff With Predictive RSS in Heterogeneous Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 6, pp. 3679–3692, 2008.

[7] A. Mishra, M. Shin, and W. Arbaugh, "An Empirical Analysis of the IEEE 802.11 MAC Layer Handoff Process," *Acm Sigcomm Computer Communication Review*, vol. 33, no. 2, pp. 93–102, 2003.

[8] S. Pack, H. Jung, T. Kwon, and Y. Choi, "A Selective Neighbor Caching Scheme for Fast Handoff in IEEE 802.11 Wireless Networks," in *Proc. ICC*, vol. 5, 2005, pp. 3599–3603.

[9] A. Mishra, M. Shin, and W. Arbaush, "Context Caching Using Neighbor Graphs for Fast Handoffs in a Wireless Network," in *Proc. IEEE INFOCOM*, vol. 1, 2004, pp. 351–361.

[10] T. M. Ali, M. Saquib, and C. Sengupta, "Performance Analysis Framework and Vertical Handover Triggering Algorithms for Voice over WLAN/Cellular Network," in *Proc. WCNC*, 2008, pp. 3186–3190.

[11] T. Ali and M. Saquib, "Analysis of an Instantaneous Packet Loss Based Vertical Handover Algorithm for Heterogeneous Wireless Networks," *IEEE Transactions on Mobile Computing*, vol. 13, no. 5, pp. 992–1006, 2014.

[12] E. Stevens-Navarro, Y. Lin, and V. W. S. Wong, "An MDP-Based Vertical Handoff Decision Algorithm for Heterogeneous Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 2, pp. 1243–1254, 2008.

[13] Y. Zhang, Y. Liu, Y. Xia, and Q. Huang, "LeapFrog: Fast, Timely WiFi Handoff," in *Proc. IEEE GLOBECOM*, 2007, pp. 5170–5174.