Modeling and Analysis of the Performance for CIS-based Bluetooth LE Audio

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Abstract—Wireless audio transmission has always been the focus of Bluetooth application scenarios. Future audio use cases, such as multi-streaming to assist stereo imaging experiences, broadcast audio sharing, hearing aid support, etc., have higher requirements for quality of service (QoS). LE Audio based on Bluetooth Low Energy (BLE) is considered to be a replacement for the Bluetooth classic audio standard in the next generation of audio applications. However, until now, the performance of CIS-based LE Audio has not been fully analyzed. In this paper, we propose a mathematical model to evaluate the performance of CIS such as packet loss rate (PLR), throughput, backlog, delay, and average power consumption. In addition, the feasibility of multi-hop transmission based on CIS is explored, and the model is extended to analyze the end-to-end PLR and throughput. Finally, the accuracy of the proposed model is verified by simulation results, and the relationship between CIS parameters and performance is analyzed, providing guidance for parameter selection in LE Audio applications.

Index Terms—Bluetooth low energy, LE Audio, isochronous stream, Markov chain, performance analysis.

I. INTRODUCTION

In recent years, with the rise of audio-related application scenarios such as stereo audio [1], hearing aids [2], and audio sharing [3], people have put forward higher requirements for wireless transmission mode and quality of service (QoS) of audio [4]. Low energy (LE) Audio based on Bluetooth low energy (BLE) released by the Bluetooth Special Interest Group (SIG) has very high potential and is considered as a replacement for Bluetooth Classic Audio. According to statistics, in 2023, 480 million devices supporting LE Audio were shipped, and SIG predicts that this number will increase to 3 billion by 2027 [5].

Fig. 1 shows the operating mode comparisons between Bluetooth Classic Audio and LE Audio, where the former is single audio stream based while the latter is multiple audio streams based. To achieve stereo stream experience based on Classic Audio, as shown in Fig. 1a, the relay and sniffer modes are introduced sequentially [6] where one earbud acts as a relay node or a controller for the other, such that the same audio stream can be received by both earbuds. To enhance the performances of Classic Audio in terms of power consumption, latency and bandwidth [7], LE Audio is introduced, whose operating modes are shown in Fig. 1b. In the connected mode, these two earbuds are formed as a connected isochronous group (CIG), each of which can send and receive an isolated connected isochronous streams (CIS) from the phone. In the broadcast mode, multiple hearing aids form a broadcast isochronous group, each of which can receive different broadcast isochronous streams (BIS) from the phone.

To overcome the unreliable transmission of the Industrial, Scientific and Medical device (ISM) band, the data-acknowledgement scheme and the n-repetition scheme are employed by CIS and BIS, respectively. Therefore, CIS can guarantee the reliability of the link to a certain extent, and is suitable for common unicast non-shared audio applications. BIS uses connectionless broadcast communication and only provides unidirectional transmission without ACK [8], which is designed for audio sharing applications. This paper focuses on modeling and analysis of the CIS performance.

To the best knowledge of the authors, the performance of CIS-based Bluetooth LE Audio transmission has not been theoretically studied and analysed. Without theoretical modeling of CIS, the impacts of the CIS parameters can only be tuned heuristically and experimentally, which heavily hinders the development of related multiple audio stream applications. This motivates us to build a mathematical model to theoretically analyse the performances of CIS, and to provide guidance on how to set the CIS parameters.

In addition, the limited communication range is one of the disadvantages of Bluetooth. Considering that multi-hop transmission is an effective way to overcome transmission range limitations both in classic Bluetooth [9] and BLE [10], multi-hop transmission based on CIS is a potential solution in the long-distance transmission scenario of audio. Therefore, it
Motivated by above observations, we theoretically evaluate and analyze the performance of single and multi-hop transmission of CIS-based Bluetooth LE Audio. The main contributions are summarised as follows.

- A 2-dimensional (2D) Markov model is proposed based on the principle of CIS to analyse performance. Five performance measures are derived, in terms of packet loss rate (PLR), throughput, backlog of the queue, average delay and average power consumption.
- A time division CIS-based multi-hop transmission method is introduced to explore the feasibility of CIS based multi-hop transmission. The packet output process of the proposed 2D Markov model is firstly studied. Then, the model is extended by considering the characteristics of the packet output process, such that the intermediate node’s packet output process can also be characterized. Finally, the PLR and the throughput of any $h$-th hop and the whole multi-hop path are derived.
- The accuracy of the proposed model is verified by comparing with simulation results. The impact of each parameter within CIS is illustrated and analyzed in details to have a clear understanding of how they affect the performance. Based on the findings, it is observed that regardless of whether it is a single-hop or multi-hop case, the PLR can approach zero within a specific range of packet error rate. Additionally, there exists a transitional phenomenon in both queue backlog and delay, characterized by rapid changes within a certain range of packet error rate. The impacts on average power consumption are also analysed.

The other sections are organized as follows. Sec. II provides the system models of the CIS. In Sec. III, a flush point conversion method is firstly presented and then the proposed 2D Markov model for the single hop case is detailed. Five performance measures are theoretically derived sequentially. Sec. IV extends the proposed 2D Markov model to the case of multi-hop, and the PLR and the throughput are theoretically derived. Sec. V presents the numerical and simulation results, insights and guidance based on which are drawn out in Sec. VI. Sec. VII overviews the Bluetooth audio background and related works. Sec. VIII concludes this paper and prospects for the future work are discussed.

II. SYSTEM MODELS

Based on the core specification of BLE5.4 [11], the CIS procedures are presented firstly in Sec. II-A. And then, the flush point assignment scheme is given in Sec. II-B.

A. BLE background and CIS procedures overview

BLE defines 40 channels in the 2.4 GHz ISM band, each with a bandwidth of 2 MHz. To improve efficiency, 3 specific channels are allocated for neighbor discovery and connection establishment. At the physical layer, BLE uses GFSK modulation mode to reduce peak power, and uses frequency-hopping technology to transmit data on the channel determined by the channel selection algorithm (CSA).

The BLE device, say mobile phone, that want to transmit and receive data from the other BLE devices, say earbuds, undergoes advertising and scanning process, for neighbor discovery and connection. Once the connection between two BLE devices is set up, they can establish a CIS to deliver audio stream. A CIS is a logical transport, which enables the transmission of isochronous data between connected devices in either direction. The initiator of CIS is also the initiator of the connection, referred to as the Central, and the peer device is referred to as the Peripheral.

![Fig. 2. Example of CIG, CIS events and subevents](image)

Let us employ the example of mobile phone connecting with earbuds again, to illustrate the terminologies associated with the CIS procedures. As shown in Fig. 2, after mobile phone $C$, acting as Central, connects with the earbuds $P1$ and $P2$, acting as Peripherals, it forms a CIG for them, containing two CISes, i.e., CIS #1 for $P1$ and CIS #2 for $P2$. Thus, one CIS can be seen as one audio stream, and all CISes, i.e., CIS #1 and #2, belonging to the same CIG have same ISO Interval $I_0$. Note that a CIG can consist of one or multiple CISes [11].

Next, the multi-audio streams are carried by the periodically occurred CIS events, CIS events and CIS subevents. For example, CIS event 1 and 2 are consecutively scheduled with interval $I_0$, and CIS #1’s subevents 1s and 2s are also occurs with intervals $I_0$, with different anchor points determined when establishing the CIS. Within each CIS event, there may exist one or multiple consecutively occurred CIS subevents, with subinterval $I_s$, the first one of which occurs from the anchor point of the CIS event. For example, in each CIS #1’s event, there are 2 subevents while only one in that of CIS #2. Let $N_S$ denote the number of CIS subevents within one CIS event. Within each subevent $s$, $1 \leq s \leq N_S$, the audio packets are transmitted from the Central to the Peripheral firstly and then feedback from the Peripheral to the Central.

At the CIS’ anchor points, a burst up to $BN$ (Burst Number) valid payloads arrive periodically, denoted as $N_B$, ranging in $[0, 15]$ as given in [11]. These payloads will be packaged into CIS Data PDU (Protocol Data Unit), which will be referred as packet or data for short in this paper, with length of $L_{\text{payload}}$ and $L_{\text{data}}$, respectively. If the source provides constant bit rate (CBR) flow, i.e. $N_B$ valid payloads arrive at the beginning of each CIS event, the data rate is $R_{\text{CBR}} = N_B L_{\text{payload}} / I_0$.

If the valid payloads are less than $N_B$, empty payloads can be supplied according to [11], to reduce waiting latency. These empty payloads will also be stamped with payload number of $C_P$. Such that, in a CIS event, there are totally $N_B$ arrived payloads, including the valid and empty ones. After all valid
payloads are delivered, or an empty payload is found, the CIS event can be closed \[11\].

For each CIS, two 39-bits counters, i.e., \(cisEventCounter\) and \(cisPayloadCounter\), are employed by both the Central and Peripheral, used to store the current CIS event index and the cumulative arrived payload number, respectively. In this paper, we use \(C_E\) and \(C_P\) to denote the value of \(cisEventCounter\) and \(cisPayloadCounter\), respectively. \(C_E\) increases from the first CIS event, i.e., 0, by 1 in each CIS event, \(C_P\) increases when a payload is supplied, no matter it being as valid or empty, which is stamped with payload number of \(C_P\). Such that, within the \(C_E\)-th CIS event, we have \(C_E N_B \leq C_P \leq (C_E + 1)N_B - 1\). We use \(A(C_P)\) to represent the CIS event number when payload \(C_p\) arrives, i.e.,

\[
A(C_P) = \left\lfloor \frac{C_P}{N_B} \right\rfloor_1. \tag{1}
\]

All packets are buffered in a FIFO queue, waiting to be transmitted during the CIS subevents. To avoid overflow and to avoid the blockage problem of HoQ, a flush point assignment scheme is specified by the core specification \[11\].

B. Flush point assignment scheme

In addition to \(N_S\) and \(N_B\), the parameter \(FT\) (Flush Timeout), denoted as \(N_F\), is additionally introduced, used to control which packets can be transmitted in each CIS event. From the viewpoint of a packet, \(FT\) can be seen as the maximum number of CIS events, during which the packet may be transmitted and retransmitted. To implement this, a flush point is assigned to each packet. It is a time point at which the packet shall be discarded if not yet successfully transmitted. Let \(F(C_P) = [E(C_P), U(C_P)]\) denote the flush point of the packet with payload number \(C_P\), which means that packet \(C_P\)'s flush point is at the ending of the \(U(C_P)\)-th subevent in the \(E(C_P)\)-th CIS event,

\[
E(C_P) = A(C_P) + N_F - 1 = \left\lfloor \frac{C_P}{N_B} \right\rfloor_1 + N_F - 1, \tag{2}
\]

\[
U(C_P) = N_S - \left\lfloor \frac{N_S}{N_B} \right\rfloor_1 (N_B - 1 - C_P \mod N_B). \tag{3}
\]

From Eq. (3), it can be found that for packet \(C_P\), at least \(\lfloor N_S/N_B \rfloor_1\) CIS subevents, or transmission opportunities (TXOP), are allocated specifically to it.

Fig. 3 shows examples of queue management and packet flush points, detailed as follows.

- Fig. 3a sets \(N_S = 4, N_B = 2\) and \(N_F = 1\), and packets \(P_1\) and \(P_2\) are dropped due to interference when their flush points arrive. At each anchor point of the first three CIS events, two packets arrive at the Central \(C\), and are buffered into the FIFO since \(N_B = 2\). Therefore, the flush points of the sequentially arrived packets of each CIS event can be calculated as \(F(0) = [0, 2], F(1) = [0, 4], F(2) = [1, 2], F(3) = [1, 4], F(4) = [2, 2]\) and \(F(5) = [2, 4]\). However, when the packets are transmitted, different cases may occur. As shown in Fig. 3a, packet \(P_1\) is successfully transmitted in the first attempt, but \(P_1\) unfortunately fails even though it consecutively attempt 3 times. Thus, upon \(F(1)\) packet \(P_1\) is discarded, and upon \(F(2)\) packet \(P_2\) is discarded due to the large interference.
- Fig. 3b sets \(N_F = 2\), different from Fig. 3a. Thus, the flush points are calculated as \(F(0) = [1, 2], F(1) = [1, 4], F(2) = [2, 2]\) and \(F(3) = [2, 4]\), which are postponed one CIS event. This difference makes packet \(P_1\) have more opportunities to be successfully transmitted, and thus no packets is discarded.

Based on above observations, the CIS-based Bluetooth LE Audio transmission system can be seen as a counter-dependent system, i.e., \(C_P\) and \(C_E\). To mathematically model the system and analyse its performance, Sec. III presents a flush point conversion scheme to transform it into a recurrent-system firstly, and then a 2D Markov model is presented.

III. 2D MARKOV MODEL OF CIS

In this section, we intend to model the performance of CIS-based Bluetooth LE Audio transmission system. Since CISes in the same CIG do not affect each other and audio applications tend to have only one source, we study a single CIS under the unidirectional CBR traffic. The basic idea is to transform the system from a counter-dependent one to a recurrent one. Sec. III-A details the flush point conversion scheme. Next, Sec. III-B presents the proposed 2D Markov model. And Sec. III-C derives the performance measures.

A. Flush point conversion method

Before modeling, we obtain two insights from the observations in Sec. II. Firstly, LE Audio can be considered as a counter-dependent system. \(C_E\) and \(C_P\) can be viewed as parameters with the first CIS event and the first payload as reference points, respectively, and the values continue to grow over time until 2\[39\]. Secondly, by the definition of \(N_F\), HoQ is blocked for a maximum of \(N_F\) events. That is, the queue length is finite, and the maximum queue length can be given as \(N_F \times N_B\). This inspires us to redefine a relative payload number \(c\) for packets in the queue, so that the state of the HoQ can be represented by \(c\), without considering \(C_E\) and \(C_P\).

Next, we formally introduce the relative payload number \(c\). Let us focus on any given CIS event, named as reference CIS event. The values of \(c\) are defined as follows.
• At the anchor points, the newly arrived packets are always numbered from 0 to \( N_B - 1 \).
• At the ending of the \( N_S \)-th subevent, the backlogged packets’ relative payload number is decreased by \( N_B \), if any.

Such that, the range of \( c \) can be bounded, i.e., \( c \in [N_B(1 - N_F), N_B - 1] \). Note that if some packet with \( c < 0 \), it means that no CIS subevents is left in the CIS event where it arrives, but it may still have opportunities to be transmitted in the following CIS subevents.

Accompanying with Eqs. (2-3), the relative flush point of a packet with relative payload number \( c \) can be calculated as

\[
F(c) = N_S \times E(c) + U(c) \\
= N_S \times \left( \frac{c}{N_B} + N_F - 1 \right) + \left( N_S - \left\lfloor \frac{N_S}{N_B} \right\rfloor \right) (N_B - 1 - c \mod N_B) \tag{4}
\]

In particular, according to (4), when \( c \in [N_B(2 - N_F), N_B - 1] \) and \( N_F > 1 \), we have \( F(c) > N_s \). This means that the flush points for these payloads are distributed in future CIS events.

Fig. 4 shows an example of the relative payload number \( c \) in CIS events, where \( N_S = 4 \), \( N_B = 2 \) and \( N_F = 2 \). At the beginning of the \( x \)-th CIS event, two new arrived packets are assigned the relative payload number as 0 and 1, respectively, and are inserted into fifo. Through Eq. (4), the relative flush points can be calculated as \( F(0) = 6 \) and \( F(1) = 8 \), respectively, i.e., in the \( (x + 1) \)-th CIS event. After 3 tempts, packet 0 is successfully transmitted, and at the ending of the 4-th subevent, the relative payload number of the backlogged packet 1, is decreased by \( N_B \) to be −1. Next, the reference CIS event moves forward as the \( (x + 1) \)-th CIS event. When entering the \( (x + 1) \)-th CIS event, the two new arrived packets are assigned the relative payload number as 0 and 1 again. Through Eq. (4), we have \( F(-2) = 2 \) and \( F(-1) = 4 \). That is, the flush point of the payloads arrived in the \( x \)-th CIS event appears in the \( (x + 1) \)-th event, conforming to \( N_F = 2 \).

![Fig. 4. Example of relative payload number \( c \) in CIS events when \( N_S = 4 \), \( N_B = 2 \), \( N_F = 2 \).](image)

**B. 2D Markov model of CIS**

Considering that the basic operation of CIS events is the packet interaction between the Central and Peripheral in subevents, the following assumptions can be made.

1) Since ACK frame is short, the transmission success probability of the ACK frame is considered to be 1.
2) The packet length of the Central is fixed to \( L^{data} \). All transmission errors of data packets are caused by interference and noise. With probability \( P_a \), one packet transmission attempt is successful.
3) The audio stream is CBR, and the burst packets arrival time is at the anchor point of each CIS events. The inter-arrival time is \( I_a \), and the batch size is \( N_B \).

A Markov process is proposed to represent the packet transmission process in a given CIS subevent. Similarly with \( c \), we define the subevent number as the relative subevent index, represented by \( s \), \( 1 \leq s \leq N_S \). \( s = 1 \) represents the first subevent of the reference CIS event, and \( s = N_S \) represents the last subevent of the reference CIS event. We define \( S = [1, N_S] \) as the value range of \( s \), i.e., \( s \in S \).

We observe the system at the beginning of each CIS subevent and describe the Markov chain state as \( \tau(s,c) \), where \( s \) is the subevent index and \( c \) represents the relative payload number of the HoQ. Let \( c = N_B \) indicate that the queue is empty. We define \( C = [N_B(1 - N_F), N_B] \) as the value range of \( c \), i.e., \( c \in C \). Then, the state space of this Markov chain can be described as

\[
D = \{(s,c) \mid s \in S, c \in C\}. \tag{5}
\]

Let the sequence of states be arranged in ascending order by comparing \( s \) first and \( c \) later. Next, the state transitions are analysed when the system evolve from CIS subevent \( s \) to \( s + 1 \), where we note that only payloads with \( F(c) \leq N_S \) are involved in the relative CIS event, and \( F(c) > N_S \) will be processed in the future CIS events.

1) If \( s < F(c) \), \( 1 \leq s < N_S \) and \( c \neq N_B \), the station will transmit the HoQ packet. \( s \) will evolve to \( s + 1 \) and \( c \) may be increased by 1 with probability \( P_b \).
   a) With probability \( 1 - P_a \), the state transits to \((s + 1, c)\) if the packet is not successfully transmitted.
   b) With probability \( P_a \), the state transits to \((s + 1, c + 1)\) if the packet is successfully transmitted.

2) If \( s < F(c) \), \( s = N_S \) and \( c \neq N_B \), the reference CIS event will be closed after this transmission and start the next CIS event. Thus, \( s \) will evolve to 1, i.e., the 1-st subevent of the next CIS event, and \( c \) of the backlogged packets will be decreased by \( N_B \) and may be increased by 1 with probability \( P_b \).
   a) With probability \( 1 - P_a \), the state transits to \((1, c - N_B)\) if the packet is not successfully transmitted.
   b) With probability \( P_a \), the state transits to \((1, c - N_B + 1)\) if the packet is successfully transmitted.

3) If \( s = F(c) \), \( 1 \leq s < N_S \) and \( c \neq N_B \), this is the last transmission attempt of the HoQ packet. Regardless of whether the packet is successfully transmitted or not, it will be discarded after the current subevent. Thus, the state transits to \((s + 1, c + 1)\) with probability 1.

4) If \( s = F(c) \), \( s = N_S \) and \( c \neq N_B \), this is the last transmission attempt of the HoQ packet and the station will close the CIS event after this transmission. Regardless of whether the packet is successfully transmitted or not,
it will be discarded after the current subevent. Thus, the state transits to \((1, c - N_B + 1)\).

5) If \(1 \leq s < N_S\) and \(c = N_B\), i.e., empty queue, with probability 1 the state transits to \(\tau(s + 1, c)\).

6) If \(s = N_S\) and \(c = N_B\), i.e., empty queue, with probability 1 the station will start the next CIS event and the state transits to \(\tau(1, 0)\), where new burst packets will arrive and attempt to transmit the 1-st one.

Based on above analysis of the state transitions, one can derive the one-step state transition probability matrix, denoted as \(A\). Theorem 1 proves that above described 2D Markov chain has a single stationary probability distribution, denoted as \(\pi = [\pi_{(s,c)}], (s,c) \in D\), where \(\pi_{(s,c)}\) is the stationary probability of state \(\tau(s,c)\). Such that, \(\pi_{(s,c)}\) can be numerically derived by solving the following linear equations,

\[
\begin{align}
\pi = \pi A, \\
\sum_{(s,c) \in D} \pi_{(s,c)} = 1.
\end{align}
\]

**Theorem 1** If \(0 < P_s < 1\), the 2D Markov chain, described by state \(\tau(s,c)\), state space \(D\) in Eq. (5) and one-step state transition probability matrix \(A\), has a single stationary probability distribution \(\pi\).

**Proof 1** On one hand, since a discrete-time Markov chain is irreducible and positive recurrent, it has has a unique stationary distribution. On the other hand, since a finite-state chain Markov chain is irreducible, it must be positive recurrent. And the proposed 2D Markov chain is a discrete-time finite-state one, we only need to prove it is irreducible.

Note that a Markov chain is said to be irreducible when it is possible to reach any state from any other state. To prove that, we denote state \(\tau(1,0)\) as the basic state, and the initial state of every CIS is \(\tau(1,0)\). Therefore, one can find that from the basic state, any other state can be reached by several steps with a non-zero probability since \(P_s < 1\).

In addition, since when \(P_s > 0\), any state can be transited to state \((N_S, N_B)\) after several steps, where recall that \(c = N_B\) denotes the empty queue. And state \(\tau(1,0)\) can be transited from \((N_S, N_B)\) with probability 1, so any state can be transited to the basic state, which completes this proof. ■

**C. Performance measures**

Based on the stationary probability of state \(\tau(s,c)\), i.e., \(\pi_{(s,c)}\), the performance measures of CIS-based Bluetooth LE Audio transmission system are derived as follows.

1) **Packet Lost Rate:** We note that the event of discarding packet \(c\) can only occur when \(s = F(c)\) and packet \(c\) is still transmitted unsuccessfully, with probability \((1 - P_s)N_S\pi_{(F(c),c)}\). Therefore, PLR can be found as follows

\[
PLR = \frac{(1 - P_s)N_S \sum_{c \in C} \pi_{(F(c),c)}}{N_B},
\]

where \(c_1 = N_B(1 - N_F)\), \(c_2 = N_B(2 - N_F)\). \(c_1\) and \(c_2\) represent the minimum and maximum values of the relative numbers of packets, whose flush points are distributed in the current CIS event, respectively.

2) **Throughput:** Throughput is defined as the average effective bits successfully transmitted per unit time. Note that \(N_B\) packets arrive per CIS event, and the PLR can be obtained from Eq. (7). Thus, throughput can be calculated as

\[
\Gamma = \frac{N_B(1 - PLR)L_{\text{payload}}}{I_o}
\]

where \(L_{\text{payload}}\) represents the length of the payload field in the data packets.

3) **Backlog:** Since the relative number of the tail packet is \(N_B - 1\), the backlogged packets number in the system can be calculated with \(c\). Fig. 5 shows an example of backlogged packets number varies along time, which includes three cases. The first is when \(2 \leq s \leq N_S\), the backlogged packet number can be calculated as \(N_B - c\), as shown in Fig. 5, where \(N_B - c_2\) and \(N_B - c_3\) denote the number of backlogged packets, \(c_2\) and \(c_3\) being the relative payload number of the 2-nd and 3-rd subevent, respectively. The duration ratio of this case is \(N_S I_o / I_o\). The second case is when the \(N_S\)-th subevent ends but the next CIS event does not start, all the backlogged packets’ relative payload number, say \(c_1\), should minus \(N_B\). Thus the backlogged packet number can be calculated as \(N_B - (c_1 - N_B) = -c_1\), as shown in Fig. 5. The last case is when \(s = 1\) at the start of the 1st subevent a new batch arrives. Therefore, the mean backlogged packet number in the system can be expressed as follows

\[
L = \sum_{s=2}^{N_S} \frac{N_S \cdot I_o}{I_o} \sum_{c \in C} (N_B - c) \pi_{(s,c)}
- \frac{N_S (I_o - (N_S - 1) I_o - T_{\text{sub}})}{I_o} \sum_{c \in C} c \pi_{(1,c)}
+ \frac{N_S \cdot T_{\text{sub}}}{I_o} \sum_{c \in C} (N_B - c) \pi_{(1,c)}
\]

where recall that \(T_{\text{sub}}\) indicates the transmission duration of a data packet.

4) **Delay:** Since the input flow is CBR, the average arrival rate of the packet can be expressed as \(\lambda_{\text{CBR}} = \frac{N_B}{I_o}\). According to the Little’s Law and (9), we can obtain the mean time per packet in the system as follows,

\[
W = \frac{L}{\lambda_{\text{CBR}}} = \frac{I_o}{N_B} \times L.
\]

Note that the mean time per packet spent within the queue system, is equal to the time duration, from the instant when the packet enters to that when it departures.
5) Average power consumption: Since we specify that the HoQ packet’s relative payload number \( c = N_B \) indicates that there are no packets left in the system, the state \((s, N_B)\) indicates that the system is in subevent \( s \) and inactive. The conditional probability that the system is inactive in subevent \( s \) is \( N_S \times \pi_{(s,N_B)} \). Furthermore, we note that when \( N_B < s < N_S \), the probability that the next state of \((s, N_B)\) is \((s + 1, N_B)\) is \( 1 \). Therefore, when \( N_B < N_S \), the probability distribution function for the device to become inactive after the \( s \)-th subevent, which is active, is given as

\[
Q(s) = \begin{cases} 
N_S \times \pi_{(s+1,N_B)} & \text{if } s = N_B \\
N_S \left( \pi_{(s+1,N_B)} - \pi_{(s,N_B)} \right) & \text{if } N_B < s < N_S, \\
1 - N_S \times \pi_{(N_S,N_B)} & \text{if } s = N_S, \\
0 & \text{otherwise.}
\end{cases}
\]

When \( N_B = N_S \),

\[
Q(s) = \begin{cases} 
1 & \text{if } s = N_S, \\
0 & \text{otherwise.}
\end{cases}
\]

Thus, we can find the mean number of active subevents in a CIS event as follow

\[
N^{Active} = \sum_{s=N_B}^{N_S} s \times Q(s).
\]

In this paper, only the transmitted and received energy consumption in active subevents is considered, where the energy cost of inactive ones are ignored. By employing Eq. (13), the average power consumption \( P \) can be represented as follows

\[
P = \frac{E_{sub}}{I_o} \times N^{Active}
\]

where \( E_{sub} \) represents the energy consumption within an active subevent, the components of which are given as follows. Since we have ignored the energy in the inactive state, an active subevent can be divided into several stages in the case of Central, i.e., pre-processing before a subevent, packets transmission, switching to reception, receiving ACK, and post-processing before the subevent ends. For Peripherals, transmission and reception are interchanged. The energy consumption of each stage is denoted by \( E_{pre} \), \( E_{tx} \), \( E_{tr} \), \( E_{rx} \), and \( E_{post} \) respectively. Thus, in the case of Central, the energy consumption of an active subevent can be expressed as

\[
E_{sub} = E_{pre} + E_{tx} + E_{tr} + E_{rx} + E_{post},
\]

where \( E_{tx} \) and \( E_{rx} \) can be further written as

\[
E_{tx} = T_{data} P_{tx},
\]

and

\[
E_{rx} = T_{ack} P_{rx},
\]

where \( T_{data} \) and \( T_{ack} \) represent the transmission time of data packets and ACK respectively, and \( P_{tx} \) and \( P_{rx} \) represent the power of transmission mode and reception mode respectively.

IV. MULTI-HOP TRANSMISSION BASED ON CIS

In this section, we extend the model from Sec. III to multi-hop transmission. Firstly, a time division CIS-based multi-hop transmission method is introduced in Sec. IV-A. Since the \( h \)-th hop’s output traffic acts as the \((h+1)\)-th hop’s input, Sec. IV-B models the output traffic process as a variable bit rate (VBR) traffic. Such that, based on the extended Markov model for VBR traffic presented in Sec. IV-C, the performances of the time division CIS-based multi-hop transmission can be iteratively derived in Sec. IV-D, including that of any given \( h \)-th hop and the whole multi-hop route path.

A. Time division CIS-based multi-hop transmission method

Assume that there exists a pre-defined route path between the source and the destination, which includes multiple intermediate relay nodes. In the introduced time division CIS-based multi-hop transmission method, these relays start to schedule the next hop CIS event at the end of the previous hop CIS event duration, to efficiently forward packets and avoid scheduling conflicts. From the viewpoint of the whole route path, the \((h+1)\)-th hop’s CIS event does not overlap with that of the \( h \)-th hop’s and that of \((h+2)\)-th hop’s. All nodes on the route path have same CIS event interval \( I_o \), and do not overlap with their immediately adjacent nodes on the route path.

Fig. 6 shows an example, where only the first three hops are contained. Source node \( S \) successfully transmits \( P_0 \) and \( P_1 \) to node \( R_1 \) on the 1-st CIS event of the 1-st hop’s CIS event. These two payloads then continue to be labelled \( P_0 \) and \( P_1 \) by \( R_1 \). Unfortunately, \( P_0 \) fails in the CIS of the 2-nd hop and is discarded. Next, packet \( P_1 \) is re-marked as \( P_0 \) at \( R_2 \), and let \( P_1 \) act as an empty payload, to ensure that \( C_P \) is assigned sequentially. According to the core specification [11], when \( R_2 \) find \( P_1 \) is empty, it can optionally stop and close this CIS event, or it can send a CIS Null PDU instead.

Two observations can be found from Fig. 6. Firstly, even if source node \( S \) is supplied with CBR audio stream, the intermediate relays \( R_1 \) and \( R_2 \) may be supplied with VBR one due to packet loss. This motivates us to extend the proposed 2D Markov model in Sec. III-B to the case of VBR traffic. Secondly, one can find that there exists a coupled relationship between the \((h+1)\)-th hop and the \( h \)-th one, since the output traffic of the \( h \)-th hop acts as the input traffic of the \((h+1)\)-th hop. Therefore, if the output traffic of the \( h \)-th hop can be characterized as a VBR traffic, the CIS performances can be iteratively derived. Based on these two observations, Sec. IV-B characterize the output traffic process, and Sec. IV-C presents the extend Markov model for the VBR traffic.

B. Modeling the output traffic as VBR

As shown in Fig. 6, from any given node’s viewpoint of the route path, one can found that the routed traffic arrive periodically, with interval of \( I_o \). This discloses that there exists a common feature between the CBR and VBR, i.e., periodically arrived. Simultaneously, their difference can also be found that the arrived packets number of CBR is constant while that of VBR is variable. Furthermore, the arrived packets...
number of \((h + 1)\)-th hop’s is different from that of the \(h\)-th hop’s. This inspires us to define a unified VBR model to characterize any given \(h\)-hop’s output traffic process, no matter its input traffic is CBR or VBR.

In the current CIS event, the probability that \(\kappa\) packets are successfully transmitted is denoted as \(p^\text{out}_\kappa\). Since there are totally \(N_S\) CIS subevents and at most one packet can be successfully delivered, thus we have \(\kappa \in [0, N_S]\). Therefore, if the distribution of \(\{p^\text{out}_\kappa\}_{\kappa=0}^{N_S}\) can be obtained, the output traffic process characteristics of any given node on the route path can be captured.

Next, let us derive \(\{p^\text{out}_\kappa\}_{\kappa=0}^{N_S}\) of the first hop. As our observation object becomes the entire CIS event rather than subevents, the 2D Markov chain model in Sec. III can be simplified to a one-dimensional Markov chain model, with state of \(\tau(c)\), where \(c\) is HoQ’s relative payload number waiting to be transmitted in the 1-st subevent. Such that the stationary state probability of \(\tau(c)\), \(\pi_c\), can be calculated as conditional probability,

\[
\pi_c = \frac{\pi_{(1,c)}}{\sum_{s=1}^{N_S} \pi_{(s,c)}}. \tag{18}
\]

Then, \(p^\text{out}_\kappa\) can be calculated as

\[
p^\text{out}_\kappa = \sum_{c \in C} \pi_c p_{c,\kappa}, \tag{19}
\]

where \(p_{c,\kappa}\) denotes the probability of \(\kappa\) packets being successfully transmitted, with HoQ’s relative payload number \(c\).

Similar with [12], even if we cannot directly obtain information of \(p_{c,\kappa}\), we can use the transitions labelling method to find \(p_{c,c’,\kappa}\), such that \(p_{c,\kappa}\) can be represented as follows

\[
p_{c,\kappa} = \sum_{c’ \notin C} p_{c,c’,\kappa}. \tag{20}
\]

where the probability \(p_{c,c’,\kappa}\) denote that \(\kappa\) packets are successfully transmitted, when state \(c\) transits to state \(c’\). Details of applying the labelling method to calculate \(p_{c,c’,\kappa}\) are referred to Appendix A.

Therefore, by substituting Eqs. (20) and (18) into (19), the distribution of \(\{p^\text{out}_\kappa\}_{\kappa=0}^{N_S}\) can be calculated.

C. Extended Markov model of CIS for VBR

From Sec. IV-B, it can be seen that the output flow of the first hop in CIS based multi hop transmission can be regarded as a VBR flow. Therefore, we need to extend the model to the VBR traffic flow. The distribution of the input flow’s batch size for the \(h\)-th hop \(\{p^\text{in}_\kappa\}_{\kappa=0}^{N_S}\) is required.

We still observe the system at the beginning instant of each CIS subevent and describe the Markov chain state as \(\tau(s, c, m)\). \(s\) is the subevent index and \(c\) represents the relative payload number of HoQ packet. \(m\) is the number of remaining packets in the queue. Note that when \(m = 0\), \(c\) represents the expected relative payload counter number for the next packet. Thus, we define \(M = [0, N_B N_F]\). The state space of this Markov chain can be described as

\[
E = \{ (s, c, m) \mid s \in S, c \in C, m \in M \}. \tag{21}
\]

Similar to the CBR model, let the sequence of states be sorted in ascending order by comparing first \(s\), then \(c\), and finally \(m\).

Assume that the system is in state \(\tau(s, c, m)\), then the possible state transitions and their probabilities when the system evolve from \(s\) to \(s + 1\) can be derived as follows.

1) If \(s < F(c), s < N_S\) and \(m \neq 0\), the HoQ will be transmitted, after which the system state will transmit.
   a) With probability \(1 - P_s\), it transits to \(\tau(s+1, c, m)\) if the packet is not successfully transmitted.
   b) With probability \(P_s\), it transits to \((s+1, c+1, m-1)\) if the packet is successfully transmitted.

2) If \(s < F(c), s = N_S\) and \(m \neq 0\) the CIS event will be closed after this transmission and start the next one.
   a) With probability \(1 - P_s\), the state transits to \((1, c - N_B, m + \kappa)\) with conditional probability \(p^\text{in}_\kappa\), if the packet is not successfully transmitted.
   b) With probability \(P_s\), the state transits to \((1, c - N_B + 1, m - 1 + \kappa)\) with conditional probability \(p^\text{in}_\kappa\), if the packet is successfully transmitted.

3) If \(s = F(c), s < N_S\) and \(m \neq 0\), this is the last transmission attempt of the HoQ packet. Regardless of whether the packet is successfully transmitted or not, it will be discarded after this subevent. Thus, the state transits to \((s + 1, c + 1, m - 1)\) with probability \(1\).

4) If \(s = F(c), s = N_S\) and \(m \neq 0\), this is the HoQ’s last transmission attempt and the CIS event will be closed.
after this transmission. Regardless of whether the packet is successfully transmitted or not, it will be discarded after the current subevent. Thus, the state transits to 
\((1, c - N_B + 1, m - 1 + \kappa)\) with probability \(p_k^{in}\).
5) If \(s < N_S\) and \(m = 0\), i.e., empty queue, with probability 1 the state transits to \((s + 1, c, 0)\).
6) If \(s = N_S\) and \(c = 0\), i.e., empty queue, the station will start the next CIS event.

a) If \(c - N_B < N_B(1 - N_F)\), this means that there are packets that were discarded due to timeout in the previous hop. The relative payload counter of the current hop needs to be filled up. Thus the state transits to \((1, N_B(1 - N_F), \kappa)\) with probability \(p_k^{in}\).

\[ (1 - P_s) N_S \sum_{c_{min}}^{c_{max}} \sum_{s_{min}}^{s_{max}} \pi_{(c,c,m)} \] 

\[ \sum_{k=0}^{s_{max} - s_{min} + h} k p_k^{in} \]  

**Theorem 2** If \(0 < P_s < 1\), the Markov chain, described by state \(\tau(s,c,m)\), state space \(E\) and one-step state transition probability matrix \(B\), has a single stationary probability distribution.

**Proof 2** Since batch sizes are independent and identically distributed random variables, we consider a subchain of this Markov chain, which corresponds to batches of size \(\kappa\) arriving at the queue. By applying Theorem 1 and setting \(N_B = N_S\), we have that this subchain is irreducible. Therefore, this complete Markov chain is also an irreducible chain, which completes this proof.

### D. Performance measures

1) **PLR and Throughput of the \(h\)-th Hop**: Same as CBR flow, the event of discarding packet \(c\) can only occur when \(s = F(c)\) and packet \(c\) is still transmitted unsuccessfully. Therefore, the PLR of \(h\)-th hop can be found as follows

\[
PLR_h = \frac{(1 - P_s) N_S \sum_{m=1}^{m_{max}} \sum_{c_{min}}^{c_{max}} \pi_{(F(c),c,m)}}{\sum_{k=0}^{\frac{N_S}{\kappa p_k^{in}} - 1} k p_k^{in} - h} \tag{22}
\]

where \(m_{max} = N_F \times N_B, c_{min} = N_B(1 - N_F),\) and \(c_{max} = \min(N_B(2 - N_F) - 1, N_B - m)\). The throughput of \(h\)-th hop can be calculated as

\[
\Gamma_h = \frac{(1 - PLR_h) L_{payload} \sum_{k=0}^{N_S} \kappa p_k^{in} - h}{I_o} \tag{23}
\]

2) **PLR and Throughput under Multihop Transmission**: Like the CBR model, the output flow of the VBR model is also VBR. Therefore, the method described in Sec. IV-B can be used to obtain the output flow of the \(h\)-th hop \((h > 1)\). Then the output of the \(h\)-th hop is then treated as the input of the \((h+1)\)-th hop. Finally, the end-to-end PLR of the link with \(H\) hop can be recursively calculated as

\[
PLR = 1 - \prod_{h=1}^{H} (1 - PLR_h) \tag{24}
\]

where \(PLR_1\) can be calculated by the CBR model and (7), while \(PLR_{h>1}\) can be calculated by the VBR model and (22). The end-to-end throughput is equal to the throughput of the last hop, that is

\[
\Gamma = \Gamma_H. \tag{25}
\]

### V. PERFORMANCE EVALUATIONS

#### A. Simulation Settings and Validity Check of Model

In order to verify the accuracy of the proposed 2D Markov model of CIS and the multi-hop transmission model based on CIS, a simulation platform based on Network Simulator version 3 (NS-3) is developed. We simulate 1,000,000 CIS events and observe the performance under different \(N_S, N_B, N_F\), and \(P_s\). The simulation results are shown in Figs. 7-13. Other parameters that are not mentioned in Fig. 7-13 are shown in Table I. An explanation of the parameter settings, including the limitations of Bluetooth Core specification [11], is as follows. We set the transmission rate \(V\) to 2 Mbps, corresponding to the LE 2M PHY mode. When the LE 2M PHY is selected, the ACK size \(L_{ack}\) is fixed at 11 bytes (including a 16-bit Preamble). The size of the data packet is between 11 and 267 bytes, where the size of the payload field is less than 251 bytes. In the experiment, we set the packet length \(L_{data}\) to 161 bytes, which means the payload is 150 bytes. \(T_{sub}\) can be calculated by \(L_{payload} + T_{IFS} + 15\) ms. \(I_o\) shall be a multiple of 1.25 ms and between 5 ms and 4 s. \(I_s\) shall be at least \(T_{sub}\) and less than \(\frac{1}{V}\). We set \(I_o\) and \(I_s\) to 15 ms and 1 ms respectively, that is, \(N_S\) is at most 15. Based on [13], we used the following parameters to obtain the energy consumption: 8.84, 0.78, 7.03 in mA for \(E_{pre}, E_{tx},\) and \(E_{post}\), respectively, while \(P_{tx}\) and \(P_{rx}\) are fixed at 17.5 mA. Thus, \(E_{sub}\) can be calculated by (15).

To evaluate the accuracy of the two proposed Markov models, we compared the calculation results of (7)-(14), (24)
Fig. 7. Packet loss rate under different transmission success probabilities: Analysis(anal.) vs. Simulation(sim.). (a) Cases of various $N_S$ with $N_B = 2$ and $N_F = 2$. (b) Cases of various $N_B$ with $N_S = 4$ and $N_F = 2$. (c) Cases of various $N_F$ with $N_S = 4$ and $N_B = 2$.

Fig. 8. Throughput under different transmission success probabilities: Analysis(anal.) vs. Simulation(sim.). (a) Cases of various $N_S$ with $N_B = 2$ and $N_F = 2$. (b) Cases of various $N_B$ with $N_S = 4$ and $N_F = 2$. (c) Cases of various $N_F$ with $N_S = 4$ and $N_B = 2$.

and (25) with their corresponding simulation results. As shown in Figs. 7-11, the model analysis results of CIS based on CBR flow are very consistent with the simulation results. As shown in Fig. 12 and 13, there exists a little gap between the analysis and simulation results of multihop transmission.

B. Impact of Parameters on Performance

The impacts of $N_S$, $N_B$, $N_F$, and $P_s$ on both single and multi-hop CIS performances are examined as follows.

1) PLR: Fig. 7 shows the PLR for CIS. As shown in Fig. 7a, the PLR is lower in the case of a larger $N_S$, when other parameters are constant. This is because the larger the $N_S$, the larger the interval between flush points, as shown in Eq. (3).

Similarly, as shown in Fig. 7b, the case with a smaller $N_B$ has a lower PLR. However, when $N_F$ increases, it can be seen from Fig. 3 that the interval between flush points does not change, but the position of the corresponding flush points will shift to the direction of time increase. Therefore, a larger $N_F$ will provide greater fault tolerance for packet transmission, but unlike the impact of $N_S$ and $N_B$, the number of TXOPs will not be significantly improved.

As shown in Fig. 7c, the increase of $N_F$ can improve the performance of PLR, but it is not as obvious as $N_S$ and $N_B$. In addition, for the special case where $N_S$ is equal to $N_B$, the interval of the flush points is $I_s$, and PLR is equal to the probability of packet transmission error, that is, $1 - P_s$. Note that for the case where $N_S \neq N_B$, there is a range of $P_s$ that makes the PLR close to 0. For example, in the case of $N_S = 4$ and $N_B = 2$ in Fig. 7a, when $P_s = 0.7$, the PLR can be approximately equal to 0. This is a positive sign for parameters setting in LE Audio applications. According to the current channel conditions, we can select a set of appropriate CIS parameters to achieve an approximate performance of zero packet loss.

2) Throughput: Fig. 8 shows the throughput of CIS. According to equation (8), we can see that the throughput on $N_S$ and $N_F$ presents a trend opposite to the PLR. When other parameters are held constant, greater throughput can be caused by larger $N_S$ (see Fig. 8a) or larger $N_B$ (see Fig. 8b) or larger $N_F$ (see Fig. 8c). And based on (8), the upper bound of throughput is $\Gamma_{ub} = L_{payload} \cdot I_o \cdot N_B$, which corresponds to the case where PLR is equal to 0 and corresponds to the upper bound of curves in Fig. 8.

3) Backlog and Delay: Fig. 9 shows the mean backlogs of Central, and Fig. 10 shows the mean delay of packets. Based on (10), $W$ is proportional to $L$. As shown in Fig. 9a and 10a, when $P_s$ is small and $N_F$ is greater than 1, a larger $N_S$ allows packets to have more TXOPs, and packets will wait longer in the system for retransmission and cause larger backlogs. However, the opposite phenomenon occurs when $P_s$ is larger.
This is because a larger $N_S$ increases the probability that a packet will complete its transmission within one CIS event, thereby reducing latency and backlogs.

If $N_B$ is larger, the arrival rate of packets $\lambda$ will be larger, resulting in larger delay and backlog, as shown in Fig. 9b and 10b. Similarly, larger $N_F$ can cause packets to wait for more CIS events, resulting in larger delay and backlogs, as shown in Fig. 9c and 10c. In addition, as shown in Fig. 3b, $N_F$ provides $(N_F - 1)N_S$ additional TXOPs, which are shared by all packets together. When $N_S = N_B$ and there are error packets in the channel, $(N_F - 1)N_S$ error packets will exhaust the additional TXOPs, so that all subsequent packets have only one TXOP. When the channel is ideal, each packet is served at the first event after arrival, which is why the black line in Fig. 9a, 9b, 10a, and 10b mutates at $P_s = 1$.

4) Average power consumption: Fig. 11 shows the trend of average power consumption. In the special case of $N_S = N_B$, each subevent is used to transmit data, so it appears as a straight line. As shown in Fig. 11a, when $P_s$ is small, the packet needs to be retransmitted multiple times, resulting in full utilization of the subevents and stable curve. A larger $N_S$ leads to more retransmissions, which result in more active subevents. When $P_s$ is large, the packet success probability is guaranteed and the TXOPs caused by $N_S$ are no longer needed. Therefore, the curves tend to overlap.

Similarly, a larger $N_B$ means more packets, which requires the use of more subevents, as shown in Fig. 11b. A larger $N_F$ means that packets can use more CIS events. While the packet is to be discarded at small $N_F$, it can be retained at large $N_F$ and continue to attempt retransmission, thus making $P_s$ larger as shown in Fig. 11c.

5) end to end PLR: Fig. 12 shows the end-to-end PLR for a CIS-based 2 hops transmission link. The impact of parameters $N_S$, $N_B$, and $N_F$ on the end-to-end PLR of multi-hop transmissions are similar to single-hop CIS. And for given parameters, close to zero packet loss can also be achieved within a certain range of packet success probability. This means that CIS-based multi-hop transmission has a good performance in PLR and can be considered as a method to overcome the communication range limitation.

6) end to end Throughput: Fig. 13 shows the end-to-end throughput for a CIS-based 2 hops transmission link. As shown in Fig. 13a and 13c, similar to the throughput of single-hop CIS. In particular, in Fig. 13b, the effect of $N_B$ on end-to-end throughput is different from the effect on CIS throughput. When $P_s$ is smaller, the smaller $N_B$ case has greater throughput, unlike the one-hop CIS where the throughput of different $N_B$ cases is nearly the same. The difference is mainly due to the CIS of the second hop. In the above scenario, the output of the first hop is similar for
Fig. 11. Average power consumption under different transmission success probabilities: Analysis (anal.) vs. Simulation (sim.). (a) Cases of various \( N_S \) with \( N_B = 2 \) and \( N_F = 2 \). (b) Cases of various \( N_B \) with \( N_S = 4 \) and \( N_F = 2 \). (c) Cases of various \( N_F \) with \( N_S = 4 \) and \( N_B = 2 \).

Fig. 12. End to end Packet loss rate under different transmission success probabilities of 2-hop links: Analysis (anal.) vs. Simulation (sim.). (a) Cases of various \( N_S \) with \( N_B = 2 \) and \( N_F = 2 \). (b) Cases of various \( N_B \) with \( N_S = 4 \) and \( N_F = 2 \). (c) Cases of various \( N_F \) with \( N_S = 4 \) and \( N_B = 2 \).

different \( N_B \), but in the second hop, a smaller \( N_B \) can provide more TXOPs for the output flow of the first hop. For example, when \( N_S = 4 \), two different cases are \( N_B = 2 \) and \( N_B = 4 \). Assuming that two packets are successfully output within an event of the first hop, this two packets can share 4 subevents for transmission in the first case, while each packet can be transmitted only once in the second case.

VI. INSIGHT AND GUIDANCE ON PARAMETER SETTINGS

This section concludes our insights on flush point scheme in Sec. VI-A firstly, and then guidance on CIS parameters are presented in Sec. VI-B on \( N_F \) and in Sec. VI-C on \( N_S \). Note that \( N_B \) usually depend the application layer, and is directly set by the user, and thus we ignore this.

A. Flush point: a TXOP allocation and sharing scheme

We would like to highlight the main feature of the CIS-based procedures, i.e., the flush point assignment scheme, details referred to Sec. II-B. Three insights are obtained as follows.

1) Differences from \( n \)-retransmission policy, helping to guarantee delay.: In many wireless networks, the fixed TXOP allocation scheme \( n \)-retransmission policy is employed, e.g., in IEEE 802.11. In that case, a maximum retry number is assigned to HoQ, after which the HoQ will be discarded. In other words, \( n \)-retransmission policy can be regarded as a strictly TXOP allocation scheme for each packet, ignoring the dependency relationships between them. Furthermore, the allocated TXOPs are not directly related with time, and thus the delay can not be guaranteed.

However, the flush point scheme does not ignore the dependency relationships between the burst packets within the same batch, i.e., arrived at the same time, as shown in Eqs. (2) and (3) in Sec. II-B. Although a burst of packets arrives together, their flush points in time are not the same. Different numbers of TXOPs, or CIS subevents, are allocated to them. From the simulation results, one can found that this help to guarantee the average delay of the packets. We believe this insight can inspire the development of IEEE 802.11bn, Wi-Fi 8 [14], whose aims include low latency and high reliability.

2) Differences from deadline based policy, a trade-off between TXOP allocation and sharing.: The deadline based policy is also usually employed in many wireless networks. In that case, a deadline is assigned when the packet enters into the FIFO, where the queue model with impatient customers deals. Usually, the deadline, or the lifetime of the packet, is a pre-defined constant value as shown in Ref. [15]. If this policy is employed in the CIS-based audio transmission, all of the TXOPs will be shared within the batch of burst packets. Therefore, the deadline based policy can be seen as a strictly
TXOP sharing policy, where the HoQ may use up all of the TXOPs and few left for the others.

However, one can find that although the packet’s flush point is similar with deadline, it is a variable depending on \( C_p, N_S, N_B \) and \( N_F \), not a fixed one. Thus, it can achieve a trade-off between TXOP allocation and sharing. We believe that if the arrival characteristic of the traffic flow is given, there should exist some optimal flush point assignment scheme to maximize the utility of TXOP allocation and sharing. This also desires much more research efforts.

3) TXOP allocation and sharing benefit the multi-hop transmission: From Figs. 5-13, one can find that the end-to-end PLR and throughput do not reduces very much due to relay. One main reason is that the reduction of the burst packets due to packet loss, increases the average TXOPs for the successful transmitted packets, because of the flush point assignment scheme, i.e., TXOP allocation and sharing.

B. Larger \( N_F \), higher upper bound TXOPs per packet, lower PLR, higher worst case delay, but higher and \( P_s \) threshold-based linear energy consumption

From Eq. (2) and Fig. 3, one can find that for any given payload number \( C_p \), the larger \( N_F \), the latter flush point in time. In other words, if \( N_F \) is increased by 1, the flush point is postponed by one additional CIS event. That is, for some packet its upper bound TXOPs is raised up by one more CIS event, although the additional TXOPs will be shared by all of the burst of packets.

From the simulation results as shown in Figs 7-13, one can find the PLR can be reduced when \( N_F \) is increased though less obvious than \( N_S \), but at a cost of higher delay. Furthermore, from Fig. 9c, there exists a mean delay transitional phenomenon when the \( P_s \) increase from 0 to 1, for different values of \( N_F \). The transition range for different \( N_F \) almost keep unchanged, where \( P_s \in [0.3,0.7] \). If the value of \( P_s \) is lower than that range, the latency almost keep at its maximum value, depending on the value of \( N_F \). The higher \( N_F \), the higher worst case delay. Otherwise, the latency almost keep at its minimum value, irrelevant with \( N_F \).

\(^1\text{The performance differences among them demand for much more efforts, and will be studied in the future.}\)

From Eq. (11)-(14), one can find that \( N_F \) does not directly impacts on the number of active CIS subevents, or the average power consumption. However, it effects the value of \( \pi \), the stationary state probability distribution. From Fig. 10c, when \( P_s \) is larger than some threshold, there exists a linear relationship between \( N_F \) and the number of active CIS subevents, i.e., the average power consumption.

C. Larger \( N_S \), higher lower bound TXOPs per packet, lower PLR, lower worst case delay, but higher and \( P_s \) threshold-based linear energy consumption

From Eq. (3), one can find that for any given \( N_B \), the larger \( N_S \), the larger \( [N_S/N_B] \), and thus the higher lower bound TXOPs per packet. As a consequence, larger \( N_S \) can reduce the PLR, at a cost of greater power consumption. One can image that the extra consumed energy is used to re-transmit the packets, such that the PLR is reduced. From Fig. 10b, a similar \( P_s \) threshold-based linear relationships of PLR and \( N_S \) can be found. Furthermore, from Fig. 9b, a similar mean delay transitional phenomenon can be found, when the \( P_s \) increase from 0 to 1, for different values of \( N_S \). The transition range depends on \( N_S \), and the higher \( N_S \) the lower worst case delay.

VII. BACKGROUND AND RELATED WORKS

In this section, BLE Audio background is reviewed in Sec. VII-A firstly. Then, Sec. VII-B surveys the related works based on the working modes of BLE, i.e., connection and broadcast.

A. BLE Audio background

Since the birth of Bluetooth technology in 1998, wireless audio transmission has been a key focus of its application scenarios. When Bluetooth technology was first proposed, its developers identified four main use cases, three of which were related to audio: a straightforward wireless headset only used as an extension of phones, an intercom specification, and a new technology for cordless telephony [6]. Although none of these three use cases really took off at the beginning, with the increasing popularity of mobile devices and the increasing diversity of audio-related applications, Bluetooth audio transmission (based on Bluetooth Classic) gradually
became popular in the following decade, and various devices that integrated Bluetooth emerged, such as music player [16], headsets [17], and vehicle infotainment system [18]. In 2010, Bluetooth low energy (BLE) was introduced in Bluetooth core specification v4.0 [19]. As a result, Bluetooth is divided into two modes: classic Bluetooth, which includes both basic rate (BR) and enhanced data rate (EDR) modes, and BLE. Realizing that Bluetooth audio requires evolution and adaptation, Bluetooth SIG launched Basic Audio Profile v1.0 [20] as a specification for LE Audio in Sept. 2021, which defines how devices distribute and/or consume audio using BLE wireless communications (primarily CIS and BIS). Compared to Bluetooth Classic audio, LE Audio can achieve multi-stream and audio sharing, and has better sound quality and lower power consumption. The most recent BLE version is Bluetooth Core specification v5.4 [11], released in Jan. 2023, and this paper is based on the definitions in this version.

Baghel et al. [7] shared technical insights on the challenges and future works in the evolution from Bluetooth Classic Audio to LE Audio, including LC3 codecs, multi-stream audio, broadcast, and hearing aids. Focusing on BIS, Jaeho Lee [8] studied and improved the performance of the n-repetition scheme of Bluetooth broadcast audio. The author proposed an energy detection-based broadcast scheme that uses an appropriate analysis model based on stochastic methods to find the optimal number of re-transmissions. Guangyue He et al. [21] designed a QoS sensitive networking scheme based on BLE audio. They used a multi-level fuzzy comprehensive evaluation method based on the reliability of the link to select BIS or CIS transmission mode for the master and slave, and proposed a method to evaluate the importance of Bluetooth nodes as a criterion for modifying transmission mode.

B. Related works

In the following, we summarize and analyze the most meaningful related studies in the scientific literature.

On one hand, several works on neighbor discovery process (NDP) and connection, can be found in the literature. In [22–25], mathematical analysis models are proposed to evaluate the performance of NDP. Especially in [25], an analysis model called Circle is proposed, which can accurately analyze the delay of multichannel neighbor discovery under two advertising modes defined in BLE: periodic deterministic advertising (PDA) and pseudo-random delay advertising (RDA). In [26], the authors propose a novel model to evaluate the performance of the advanced NDP an extended feature in BLE5.0, and compares it with the basic NDP. Ref. [27] proposes a new scheme for BLE NDP with the wait-slot scheme based on extended advertising, and analyzes the delay and energy consumption. On the other hand, there are several existing works on the performance of BLE connection. Carles Gomez et al. [28] propose a theoretical model to analyze the maximum throughput of connection with unidirectional traffic based on the maximum number of transmissions in a connection event. In [29], the authors review the performance of BLE5.0 in terms of throughput, energy consumption, latency, etc. In our previous work [30], a 2D Markov model is proposed based on BLE5.4 to analyze the maximum throughput, duty cycle, and energy consumption of the connection. Eunjeong Park et al. [31] investigate the impact of connection parameters on performance and designed an algorithm that dynamically adjusts parameters to meet QoS requirements. In [32], the authors study the scheduling of multi-connection and propose a method to adjust the connection parameters of Peripherals to meet QoS requirements.

In addition to the research on BLE, we survey several works on periodic reservations [12], [15], [33], [34], which is due to the similarity between CIS and periodic reservations. In [33] and [34], the authors analyze multimedia stream transmission based on reserved channel access method in IEEE 802.11s mesh networks, and propose a theoretical model to analyze the PLR in noisy channel. In [12], Alexander Ivanov et al. extend the original model to analyze ordered transmission in periodic transmission opportunity (TXOP). In [15], the authors consider four different transmission modes of periodic reservation and introduce a general mathematical framework to analyze the problem of periodic reservation parameters selection.

In summary, to the best knowledge of the authors, there exists no open access literature proposed to deal with the performance of CIS-based LE Audio. Therefore, this paper proposes an efficient model to characterize the relationship between CIS parameters and performance, and to provide guidance for parameters selection in CIS-based applications.

VIII. Conclusion

In this paper, we propose a 2D Markov chain model to evaluate the performance of CIS, including the packet loss rate, throughput, backlog, delay and average power consumption. Based on it, we explored the feasibility of multi-loss transmission based on CIS, to overcome the limitations of Bluetooth transmission range. The proposed 2D Markov model is extended to multi-hop link to analyse end-to-end PLR and throughput. Finally, the accuracy of the model is demonstrated by comparing with the simulation results, and the influence of CIS parameters on the performance is analysed, which provides guidance for LE Audio application.

In future, our focus will be on investigating the impact of interference between CIS pairs on performance in dense scenarios. We will further explore performance optimization techniques for CIS and propose an efficient algorithm to achieve optimal performance by adjusting parameters such as \( N_{S}, N_{B}, N_{F} \), and transmission power. Additionally, our future work aims to develop a rigorous CIS-based multi-hop protocol.

APPENDIX A

TRANSITIONS LABELLING METHOD TO CALCULATE \( p_{c,c',\kappa} \)

Based on the 2D Markov model proposed in Sec. III-B, the one-dimensional Markov chain model can be simplified, with state of \( \tau(c) \), where \( c \) is HoQ’s relative payload number waiting to be transmitted in the 1-st subevent. Let \( R \) denote its one step state transition probability matrix. Then \( R \) can be derived from that of the 2D Markov model, i.e., \( A \).

Recall that there are \( N_{S} \) subevents in the reference CIS event, and \( A \) is the one step state transition probability matrix.
of the 2D Markov model. Thus, $A^{N_S}$ is the $N_S$-step state transition probability matrix, or the 2D Markov model's state transition probability matrix per CIS event. Then, $R$ can be derived as

$$R = \begin{bmatrix} I_x & O_{x \times y} & A^{N_S} & I_x & O_{y \times x} \end{bmatrix},$$

(26)

where $I_x$ represents a identity matrix with $x$ rows and $x$ columns, $O_{x \times y}$ represents a zero matrix with $x$ rows and $y$ columns, $x$ represents the number of states with $S = 1$, and $y$ represents the number of states with $S \neq 1$. Obviously, $A$ is a $(x + y) \times (x + y)$ square matrix, and $R$ is a $x \times x$ square matrix. Note that the sum probabilities of all transition paths between any $tw$ states is a element of $R$.

A special label $\gamma$ is multiplied with the the successful packet transmission elements of matrix $A$, such that the numerical matrix $A$ is converted into matrix $A$, and further matrix $R$ can be obtained by substituting $A$ into equation (26). Element $\hat{R}_{ij}$ of matrix $R$ corresponds to the transition from state $c_i$ to state $c_j$. This element can be expressed in polynomial form as follows

$$\hat{R}_{ij} = \sum_{\kappa=0}^{N_S} \gamma^{\kappa} p_{c_i,c_j,\kappa},$$

(27)

where $p_{c_i,c_j,\kappa}$ can be derived, which represents the probability that during the transition from state $c_i$ to state $c_j$, $\kappa$ packets are successfully transmitted.

REFERENCES


