Delay Optimal Concurrent Transmissions With Raptor Codes in Dual Connectivity Networks

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***Abstract*—Dual connectivity (DC) has been emphasized in both LTE and 5G networks to utilize a secondary evolved NodeB (SeNB) connected to the master evolved NodeB (MeNB) that can simultaneously serve the user equipment (UE) to improve the per-user throughput as well as the mobility support. However, the non-ideal X2 link between the MeNB and SeNB and the dynamic channel condition can cause severe out-of-order packet arrival problem when transmitting data to the UE via MeNB and SeNB concurrently, which leads to excessive delay and requires non-trivial effort to do the de-jitter queueing and retransmission. In this paper, we propose a Raptor codes based dual connectivity (RCDC) scheme to solve the out-of-order packet arrival problem with the reduced delivery delay. The source packets at the MeNB are coded and separately transmitted to the UE through the MeNB and SeNB. Due to the unique recover capability of Raptor codes, the UE can decode the original data if enough encoded packets are received from either the MeNB or SeNB, and thus the out-of-order problem can be effectively eliminated without a dedicated de-jitter process. Mathematical models are developed to analyze the delay performance and simulation results are provided to demonstrate that the proposed scheme can solve the out-of-order packet arrival problem with significantly reduced delay comparing with the conventional DC scheme.**

***Index Terms*—Concurrent transmissions, dual connectivity, raptor codes.**

I. Introduction

Dual connectivity (DC) network, standardized in 3GPP Release 12 [1], plays an important role in the LTE and 5G networks which can support some key application scenarios such as ultra-reliable low latency communications (URLLC), ultra dense network (UDN), etc. [2], [3]. The DC architecture allows the UE to connect two evolved NodeBs (eNBs) simultaneously with a non-ideal low capacity and high latency backhaul links between eNBs, which can improve end user throughput and reduce the delivery delay. Specifically, in the DC architecture, a UE can utilize radio resources provided by a master evolved NodeB (MeNB) and a secondary evolved NodeB (SeNB) simultaneously, which are connected via a non-ideal X2 backhaul link (as shown in Fig. 1). Due to the high throughput and traffic demand at the UE side, we focus on the 3C architecture for the downlink of the user plane [4] in which only the MeNB maintains a user plane connection toward the serving gateway (S-GW), and data from one radio bearer can be transmitted via both the MeNB and SeNB (as shown in Fig. 2(a)). The advantage of the 3C architecture is that the wireless spectrum in both MeNB and SeNB can be exploited simultaneously to support throughput-sensitive applications, e.g., AR/VR, video streaming, online gaming, vehicular communication, etc.

However, DC network cannot function well without the distributed radio resource management (RRM) and flow control of U-plane data between the MeNB and SeNB. Otherwise, the imbalanced utilization for two eNBs may bring an extra delay. Moreover, data transmission via dual channels may cause the out-of-order arrival problem due to the excessive delay from the non-ideal X2 backhaul link, as well as the dynamic traffic load of both eNBs and the channel variations between UE and eNB, and the extra time for packet retransmission, which lead to a high delay variation and cannot effectively support the edge computing and vehicular network communication scenarios in 5G networks.

A flow control algorithm for the X2 backhaul link has been studied in [5] to address these problems which proposed a heuristic mechanism where the user assists the flow control algorithm in performing a faster adjustment of the bearer split ratios. A similar problem occurs in the traditional multiple radio access technology (multi-RATs) systems, and some solutions have been proposed to address this problem by carefully controlling the traffic splitting, e.g., Opportunistic Multi-MAC Aggregation (OMMA) [6], state-independent packet dispatching (SIPD) and state-dependent packet dispatching (SDPD) policies [7], etc. However, most of these schemes can only partially alleviate the out-of-order arrival problem since the traffic can only be split over different paths in a coarse-grained manner, which cannot realize an accurate flow control for the traffic load. One exception is the SDPD policy proposed in [7], which achieves better delay performance by

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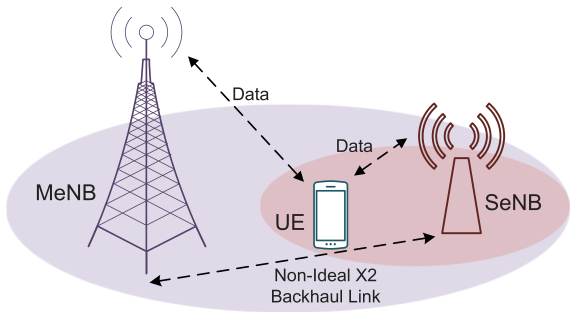
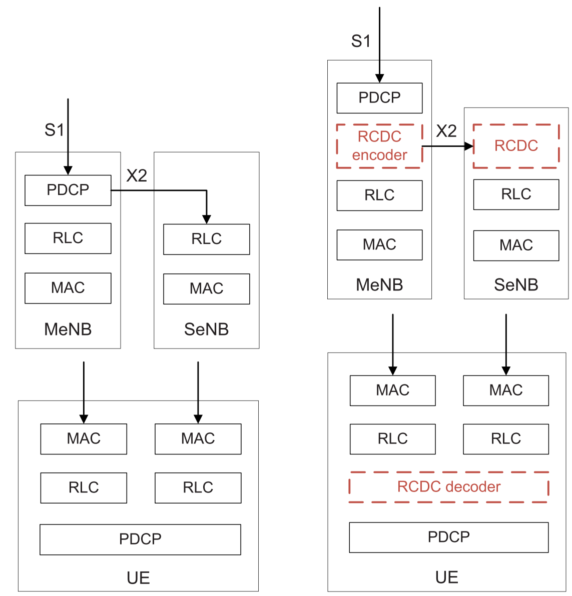


Fig. 1. Typical deployment scenario for dual connectivity networks.



(a) 3C architecture (b) Extended 3C architecture with the RCDC layer

Fig. 2. User plane architectures for dual connectivity architecture.

making online packet dispatching decisions according to the current states of all RATs. However, it introduces high signaling overhead for collecting and exchanging the state information from all RATs, which is undesired for the DC network due to the delay and bandwidth limitation over the X2 backhaul link. In [8], the network coding based schemes have also been proposed to address the complex transmission management on multiple links and optimize the delivery delay and stability. However, most of the existing studies concentrate on the multi-RATs condition which is not quite similar to the DC network, where the X2 backhaul link may cause undesirable delay and the under-utilization of the SeNB, especially for the high traffic load.

The fountain codes have been utilized in heterogeneous networks for caching and delivery the massive data with high fault-tolerance and low cost [9], [10]. As a new family of fountain codes, Raptor codes can achieve a linear encoding and decoding time complexity [11], while other coding schemes such as the random linear network coding needs to decode a batch of packets using Gaussian elimination with high time complexity, which is undesirable under a heavy traffic condition. In our recent work [12], the authors have proposed to adopt Raptor codes to address the aforementioned problems in the DC network. The basic idea is to encode the source packets at the MeNB using Raptor codes, and the encoded packets are transmitted separately through the MeNB and SeNB. Due to the unique feature of Raptor codes which only need enough encoded packets for decoding, the UE can recover the original packets as long as enough encoded packets are received from either MeNB or SeNB. Thus the packet out-of-order arrival problem can be effectively solved without complex signaling overhead between the MeNB and SeNB.

In this paper, we extend the work in [12] and propose a Raptor codes based dual connectivity (RCDC) scheme. Considering the heavy traffic load conditions and the bandwidth-consuming scenarios, we introduce an early encoding method which can improve the link utilization of the SeNB. Mathematical models are provided to analyze the performance of the proposed scheme based on the batch of arrival according to the Poisson process following the traffic load characteristics. The main contributions are summarized as follows:

- This paper proposes a novel flow control scheme in the DC network that uses Raptor codes to eliminate the out-of-order arrival problem and the retransmission, as well as to reduce the delay from variable channel states, which can support the URLLC application scenario with a high computational efficient network coding method.
- A dedicated RCDC layer is integrated into the current network stack, which is responsible for the encoding and decoding operations at the MeNB and UE respectively. In addition, we propose an early encoding method to address the under-utilization problem of the SeNB due to the X2 backhaul delay between the MeNB and SeNB.
- The queueing process is analyzed to describe the delivery delay of the proposed scheme as well as the conventional DC scheme within different parameters. Based on the mathematical model, the relationship between the block size for the encoding process and the delay performance is studied, and then an enhanced sub-block encoding scheme is proposed, which aims to find the optimal sub-block size for the Raptor codes based dual connectivity scheme to further reduce the delivery delay.
- The performance of the proposed methods are studied via the numerical results and extensive simulations, which are conducted to demonstrate that the enhanced sub-block encoding scheme achieves the optimal delay performance under different network settings.

The remainder of this paper is organized as follows. In Section II, we briefly review the related works in literature. In Section III, we introduce the RCDC protocols. Queueing models are developed for the conventional DC scheme and RCDC scheme, as well as the improvement in Section IV. Simulation results are presented in Section V to evaluate the performance of the proposed schemes. Finally, we conclude this paper in Section VI.

II. Related Work

Dual connectivity is one of the key technologies standardized in Release 12 of 3GPP specifications for the Long Term Evolution (LTE) networks [1] and the 5G networks [13], which allows the UE to connect with an MeNB and an SeNB simultaneously. The architecture and protocol for both user plane and control plane are standardized in 3GPP Release 12, in which different alternatives can be deployed in a different environment. Two different DC scenarios in which the MeNB and SeNB are on the same or the different carrier frequencies are discussed in [4], and inter-node radio resource aggregation for these scenarios are proposed to improve the user throughput. The handover enhancement based on different scenarios is proposed in 3GPP Release 13. A comprehensive overview of the standardized DC feature, the architectural enhancements as well as the detailed performance results can be found in [14].

Specifically, the problem of optimal resource allocation for traffic offloading via DC has been discussed in the literature. A flow control algorithm of data over the X2 interface is proposed in [15], which shows that the trade-off can be appropriately balanced by configuring the target buffering time in the SeNB and the flow control periodicity, which can reduce the packet scheduling overhead. In [5], [16], the authors propose an adaptive bearer split control algorithm to maximize user satisfaction and the quality of service in DC network. The authors in [17] propose an efficient scheme to minimize the total mobile data cost of the MeNB by offloading data to the SeNB, which is based on the joint optimization of the MeNB's traffic scheduling and transmitting power allocation. A downlink traffic scheduling (DTS) scheme for the MeNB is proposed in [18], in which the MeNB periodically executes the proposed DTS scheme to arrange the data rate of downlink traffic splitting to SeNBs for UEs in the DC network.

However, most of the aforementioned traffic splitting schemes in the DC network may cause the packet out-of-order arrival problem at the UE which needs to introduce an accurate flow control mechanism. Such problem has been also studied in the traditional multi-homing, multi-path routing or multiple radio access technology (multi-RATs) systems. Some transport layer solutions such as [19] and [20] have been proposed to enhance the congestion control mechanisms of the widely deployed TCP protocol with multi-homing supports in existing protocols. In MPTCP [21], multiple transport paths are used to increase the overall utilization, which requires a larger receiver buffer than that of a single-path TCP to store out-of-order packets from different paths due to the diverse characteristics of different RATs. A software defined network (SDN) based multipath control has been studied in [22], which introduces an actor-critic reinforcement learning algorithm to address the subflow congestion under highly mobile and dynamic environment. The congestion control mechanism can effectively increase the throughput but depend on a real-time environment, which need a high reliable state feedback mechanism. There are also some link layer solutions in the literature. For example, Opportunistic Multi-MAC Aggregation (OMMA) scheme [6] focuses on the multiple RATs operating on independent spectral bands, while Generic Link Layer (GLL) [23] integrates multiple RATs at the link layer to achieve better control of concurrent packet transmissions by exploiting multi-radio diversity, but it relies on the states of all links, and thus involves much higher complexity. In [24], a dynamic radio resource slicing framework for a two-tier heterogeneous wireless network is proposed which uses software-defined networking to remanage the radio spectrum resources into different bandwidth slices for different base stations which can realize a high network utility with low overhead. In [7], the online packet dispatching problem for concurrent transmission in heterogeneous multi-RAT networks is considered, and two policies, namely the state-independent packet dispatching (SIPD) and state-dependent packet dispatching (SDPD) policies, are proposed to assign the packets to different RATs according to their traffic loads and links states, such that packet reordering delay at the destination can be minimized. These schemes are either ineffective in alleviating the out-of-order problem due to coarse-grained control of the traffic splitting, or incurring high signaling overhead since the states of different paths have to be collected online. A precoding compensation scheme proposed in [25] can improve the flow control accuracy which may be impacted by some outdated information and can reduce the state exchange for different channels in the heterogeneous networks but introduce a high computational complexity.

Recently, the network coding scheme has been adopted for the multi-RAT and multi-path routing schemes to address the out-of-order arrival problem of traffic control in literature. In [26], the authors propose a network coding based multipath TCP scheme, in which the subflows deliver linear combinations of the original data, which can reduce the delay of the packets and avoid the overflow of the receiver buffer. A fountain code-based multipath TCP is proposed in [27], which can effectively mitigate the negative impact of the heterogeneity of different paths with the allocation algorithm for encoded symbols to different subflows based on the expected packet arrival time over different paths. In [8], the authors propose a framework of video streaming with multi connectivity and network coding, which mainly shows the effectiveness of network coding from several simulations. However, these schemes are based on the transport layer, which needs to address the long round trip time (RTT) and multi-hop routing problems. Most of them concentrate on the overall throughput in the system and does not specifically consider the characteristics of the DC network. The general scheme based on the network coding for reducing the de-jitter time at the UE for multi-path routing scheme is proposed in [28] which motivates us to adopt Raptor codes in the DC network. In this paper, we focus on the DC network and take into account the impact of the backhaul link. A Raptor codes based scheme is proposed to simplify the management of the transmission, enhance the utilization of the SeNB and reduce the delivery delay. Particularly, Raptor codes are used in this work to encode the original packets for the following reasons. Firstly, Raptor codes are a new family of fountain codes which is also known as rateless codes [11], [29]. The rateless property allows the UE to recover the original packets by retrieving any subset of encoded packets of a size slightly larger than the set of source packets, which is more flexible and reliable with lower communication overhead than the conventional ARQ based transmission scheme, whereby the UE missing a source packet must successfully receive another source packet it has not previously received which introduces additional overhead. Secondly, compared with other codes widely used with $O(N^3)$ complexity, e.g., random linear network codes, the fountain codes, such as LT codes, have a superior decoding time complexity of $O(N \ln N)$ [30] and Raptor codes can further reach a linear decoding time complexity $O(N)$ by introducing a precoding process [11], where N is the number of source packets to be encoded. With the Raptor codes based dual connectivity scheme, the queueing models are developed to characterize the delay performance of the proposed scheme. The enhanced scheme is proposed to optimize the network delay, and the simulation results are given based on the NS-3 network simulator.

III. Raptor Codes Based Dual Connectivity Scheme

In this paper, we focus on the downlink transmission in the 3C option of the DC networks as shown in Fig. 2(a). We assume the packets arrive at the MeNB in batch due to the characteristics of the emerging data-rich applications, such as video streaming, social messaging, etc. Packets of a batch arrival are split at the Packet Data Convergence Protocol (PDCP) layer of the MeNB, and then transmitted to the UE through the MeNB and SeNB (via the X2 backhaul) respectively.

The challenges of this DC scenario are three-folded. Firstly, the MeNB has to make judicious flow control decisions based on the states (channel condition, traffic load, etc.) of the SeNB. Therefore, the SeNB needs to report its status to the MeNB, which introduces non-trivial signaling overhead. Secondly, due to the transmission delay of the X2 backhaul link, the reported status of the SeNB may already expire, which may lead to the inaccurate control and cause the data overloaded or underflow in the SeNB. In this case, the imbalance of different links will result in the delay of a whole batch of packets. Last but not the least, the UE has to temporarily store the out-of-order packets in the de-jitter buffer, which leads to extra delay for re-ordering the packets.

Most of the current solution to address these problems in the DC network is to adjust and optimize the traffic splitting such as the SIPD scheme in [7] and the flow control algorithm in [5]. These solutions can effectively minimize the delay in the DC network and we will propose a model based on traffic splitting in Section IV-B as a comparison based on these algorithms. However, some out-of-order problems and the imbalance problems also existed since the link changes dynamically. The SDPD scheme in [7] is another solution to address such problems, which achieves a better performance since the dispatching decision is made online with real-time data. Nevertheless, it introduces a high signaling and frequent data exchanging between two eNBs, which may heavily consume the X2 bandwidth and is not desirable for the DC network.

To address the problems above, we propose a Raptor codes based dual connectivity scheme. In this section, we first introduce the network models considered in this paper, as well as the encoding and decoding procedure for the RCDC scheme, and then propose an early encoding method to address the under-utilization problem of the SeNB.

A. RCDC Model

Network coding is a packet-level coding technique [31] and it uses different algorithms to combine source packets and generate encoded packets. In the wireless network, the network coding technique can simplify the management of the transmission on multiple links and provide additional robustness [8]. As a solution, we propose to adopt Raptor codes in the DC network to encode the packets at the MeNB, which are then transmitted separately through the MeNB and SeNB to the UE.

Raptor codes are a new family of fountain codes which have the rateless property. With Raptor codes, a batch of G source packets are grouped as an entire, which will be encoded together and G is the original batch size. For each process of the encoding, the encoder in the MeNB will calculate the parameters of the encoding generator and generate the encoded packets of the original batch. From the characteristic of the encoding generator of Raptor codes, the encoded packets can be generated by several random parameters and reach an infinite number theoretically. For the decoder, due to the rateless property of Raptor codes, it can successfully recover the original batch of packets when receiving any subset of the encoded packets of size slightly larger than the set of the source packets. In this case, if some packets are lost on the transmission, it is possible to continue generating the new encoded packets without the retransmission. This is because the decoder in the UE can recover the original batch of packets as long as successfully receiving enough encoded packets regardless of some specific encoded packets. When an encoded packet is produced, it can be immediately transmitted to the UE via either the MeNB or SeNB. The decoder in UE receives the encoded packets simultaneously from two eNBs and collects the encoded packets into the buffer. As the design of the decoding algorithm of Raptor codes [11], the decoder can recover the source batch from any set of $G' = G(1+\epsilon)$ encoded symbols which is slightly larger than G, with $\epsilon > 0$. By exploiting the rateless feature of Raptor codes, the UE can decode the original packets as long as it receives enough encoded packets from either the MeNB or SeNB, and thus the packet out-of-order problem can be effectively eliminated and the flow control signaling between MeNB and SeNB can be significantly reduced. Algorithm 1 and 2 shows the process for encoding and decoding of one batch of packets at the MeNB and the UE respectively.

To this end, we introduce a Raptor codes based dual connectivity (RCDC) layer for the 3C architecture (as shown in Fig. 2(b)), which is located between the PDCP and Radio Link Control (RLC) layers to realize the encoding and decoding processes. The main functions of the RCDC layer are as follows:

- In the MeNB, the RCDC layer is responsible for querying PDCP PDUs and encoding the source packets using Raptor codes. The encoded packets are separated into

Algorithm 1. Encoding Process for One Batch of Packets in MeNB.

```
while A batch of packets queueing in the MeNB do
    Configure the encoder parameter with Raptor codes for current
    batch of packets;
    Send the parameters to the UE;
    while UE do not recover the whole batch of packets do
        Generate the encoded packets in encoder;
        Send encoded packets to the UE via either MeNB and SeNB;
    end while
    Clear all configurations of the encoder;
end while
```

Algorithm 2. Decoding Process for Encoded Packets in UE.

```
if Receive the encoding parameters of a batch of packets then
    Configure the decoder parameter with Raptor codes for current
    batch of packets;
    while UE do not receive enough encoded packets to recover the
    original batch do
        Wait for the encoded packets;
    end while
    Recover the original batch of packets;
    Clear all configurations of the decoder;
end if
```

two streams and forwarded to the RLC layer of the MeNB, as well as the RCDC layer of the SeNB via the X2 interface.

- In the SeNB, the RCDC does not involve any encoding and decoding operations, but only receive the encoded packets from the MeNB and then forward them to the RLC layer.
- In the UE, the RCDC layer takes charge of the receiving of encoded packets from its RLC layers corresponding to the MeNB and SeNB respectively. After successful decoding, it passes the packets to the PDCP layer, and sends an acknowledge (ACK) packet back to the MeNB and SeNB to notify the end of transmissions for the current block of packets.

B. Encoding and Decoding Procedures

The main flow chart of the encoding, transmission, and decoding procedures of the proposed RCDC protocol is depicted in Fig. 3 as follows:

1) Upon receiving a batch of packets from the PDCP layer, the encoder in the MeNB generates a set of encoded packets using the Raptor coding scheme. A header will be added to each packet, which contains the necessary scheme-specific parameters of source block partitioning including encoding packet identifier (ESI), source block number (SBN), and some information for forwarding error correction following the standard Raptor codes specification (e.g., RaptorQ [32]).
2) The encoded packets are separated into two streams, one is forwarded to the RLC layer of the MeNB, and the other one is forwarded to the SeNB via the X2 interface, which is finally transmitted to the UE via the MeNB and SeNB respectively.
3) After receiving a sufficient number of encoded packets from the MeNB and SeNB, the UE recovers the entire block of source packets, and then sends an ACK back to both MeNB and SeNB.
4) Finally, upon receiving the ACK from the UE, both the MeNB and SeNB terminate the transmissions of encoded packets belonging to the current block, and then proceed to the transmissions of the next block of packets.

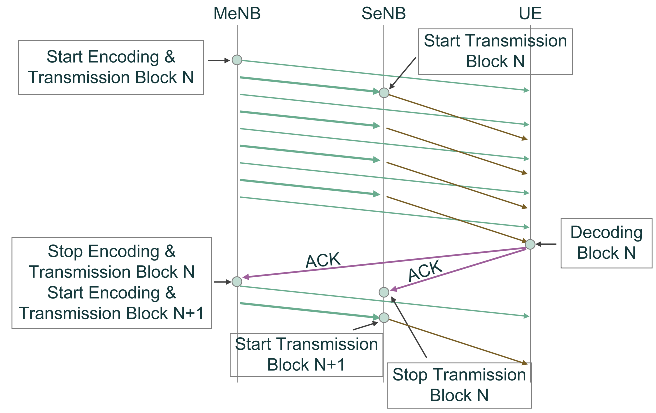


Fig. 3. Flow chart of the encoding, transmission and decoding procedures in the RCDC protocol.

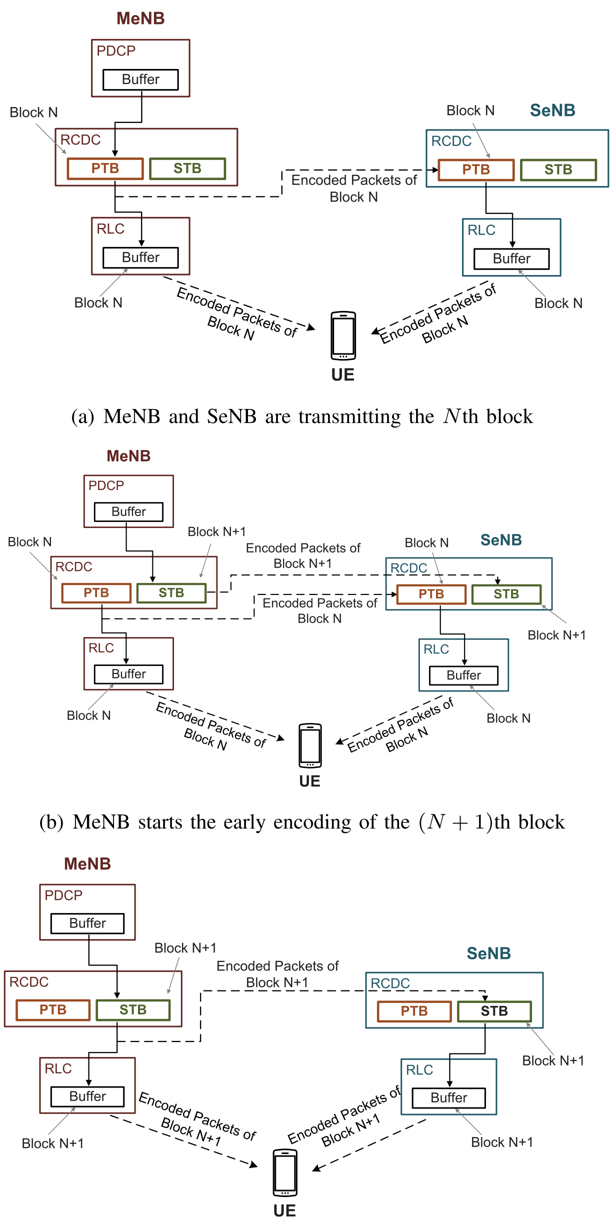
C. Early Encoding Method

Following the transmission procedures introduced in the previous subsection, after receiving the ACK from the UE, both the MeNB and SeNB stop the transmission of the encoded packets of the current block, and then the MeNB proceeds to encode the next block of packets. Due to the delay over the non-ideal X2 interface between the MeNB and SeNB, the SeNB will have no packets to transmit before receiving the next block of encoded packets, which is a waste of the wireless resource of the SeNB, especially when the traffic load is high.

To address the under-utilization of the SeNB, we propose an early encoding method at the MeNB. Specifically, when the next block of packets arrive at the MeNB before it receives the ACK of the current block from the UE, the MeNB can start the encoding of the next block of packets and forward them to the SeNB. These early encoded packets are stored temporarily at the RCDC layer of the SeNB. In this way, once the ACK is received from the UE, the SeNB can start the transmission of the encoded packets of the next block without waiting for the MeNB, and thus the idle problem of the SeNB can be avoided.

To this end, we introduce two buffers, the primary transmission buffer (PTB) and the secondary transmission buffer (STB), in the MeNB and SeNB respectively. The encoded packets of the current block are stored in the PTB, while the early encoded packets of the next block are stored in the STB of both the MeNB and SeNB respectively.

The early encoding procedure is shown in Fig. 4, which proceeds as follows:



(a) MeNB and SeNB are transmitting the Nth block

(b) MeNB starts the early encoding of the $(N+1)$th block

(c) After receiving the ACK, MeNB and SeNB start the transmission of the $(N+1)$th block

Fig. 4. Early encoding procedure.

1) Suppose that the MeNB and SeNB are transmitting the Nth block, and the MeNB has not yet encoded the next block (as shown in Fig. 4(a)), the packets of the Nth block is delivered to the SeNB via the X2 interface, which is cached in the PTB. Meanwhile, the STB is empty in both the MeNB and SeNB.
2) As shown in Fig. 4(b), the MeNB and SeNB are still transmitting the Nth block. Meanwhile, the next block of packets arrive, which are encoded and forwarded to the SeNB, and then temporally stored in the STB in the SeNB, as well as the MeNB.
3) The UE receives enough encoding packets of the Nth block, an ACK is sent back to the MeNB and SeNB. Then the encoded packets in the PTB of the MeNB and SeNB are entirely flushed, and the encoded packets of next block in the STB can be transmitted immediately (As shown in Fig. 4(c)).

With the early encoding method, we can neglect the encoding time of one batch of packets under the heavy traffic load condition. Therefore, the decoding time is the only one we need to consider in the whole transmission process, which is on the order of 10^{-5}s to 10^{-4}s [33] and is much smaller than the transmission time of a packet with the order of 10^{-3}s. Therefore, the RCDC scheme can effectively eliminate the delay from the retransmission in the conventional DC scheme.

IV. Theoretical Analysis of Queueing Models

In this section, we develop queueing based analytical model to characterize the delay performance of the conventional DC as well as our proposed RCDC scheme, and provide some numerical results to investigate the performance of these two schemes under different batch size conditions.

A. Problem Formulation

Following the networking architecture and traffic model introduced in the previous section, we assume that the batch of packets arrive at the MeNB according to a Poisson process with the arrival rate of λ and batch size of G packets, in which we assume that all packets have the same size. We mainly consider the theoretical analysis based on the heavy traffic load conditions, so that the early encoding method is deployed for the RCDC scheme.

We assume that the packet transmissions are scheduled in time slots. In the theoretical analysis, the wireless links between the eNBs and UE can be modeled as a binary erasure channel [34], thus the packet transmission can be either successful or failed in each time slot. Let r_j denote the probability that a packet transmitted by eNB j will be received successfully by the UE (i.e., r_1 indicates the successful probability of MeNB and r_2 for SeNB). The time elapsed between two successful receptions is geometrically distributed. Let X_j denote the service time for a packet (i.e., the number of time slots needed for the successful transmission of the packet), then the probability distribution for X_j is given by:

$$P(X_j = k) = r_j(1-r_j)^{k-1}, \quad k = 1, 2, \ldots \tag{1}$$

The expected service time $\mathbb{E}[X_j]$ and the second moment $\mathbb{E}[X_j^2]$ of X_j can be obtained as:

$$\mathbb{E}[X_j] = \frac{1}{r_j}, \quad \mathbb{E}[X_j^2] = \frac{2-r_j}{r_j^2}. \tag{2}$$

The main definition of the notations used in this paper are shown in TABLE I.

B. Queueing Model for DC Scheme

In the conventional DC scheme, each batch of packets arrive at the PDCP layer of the MeNB, and then are transmitted to the RLC layer of the MeNB and SeNB according to the flow control

TABLE I
NOTATIONS USED IN THIS PAPER

Notations	Description
λ	Traffic arrival rate
ϕ_j	Percentage of packets in a batch to be dispatched to eNB j
r_j	Reception probabilities at eNB j for each time slot
ρ_j^d	Traffic intensity at eNB j in the DC
ρ_r	Traffic intensity in the RCDC
ρ_{sub}	Traffic intensity in the RCDC-OB
G	Number of packets in one batch
N_G	Number of encoded packets needed for decoding in RCDC
K	Sub-block size in RCDC-OB
X_j	Service time for a packet in eNB j in DC
T_{X2}	X2 backhaul link delay in DC
T_i	First-passenger time from state i to 0 in markov chain
H_i	Generating function of T_i
$\mathbb{E}[X_j]$	First moment of X_j
$\mathbb{E}[X_j^2]$	Second moments of X_j
$\mathbb{E}[T_{N_G}]$	Mean service time for a batch of packets in the RCDC
$\mathbb{E}[T_{N_G}^2]$	Second moment of T_{N_G}
D_j^d	Mean delivery delay at eNB j in DC
D_r	Mean delivery delay in RCDC scheme
D_{sub}	Mean delivery delay in RCDC-OB scheme

algorithm. As shown in Section III, we consider the state-independent packet dispatching (SIPD) policy proposed in [7] as a basic DC scheme, which is a passive method to reach the optimal delivery delay, and then take into account the X2 backhaul delay in the DC network. Specifically, let ϕ_j denote the percentages of packets to be dispatched to eNB j (i.e., $j=1$ for MeNB, and $j=2$ for SeNB, and $\phi_1+\phi_2=1$), then the traffic of eNB j is still a Poisson batch arrival process with the batch arrival rate λ and batch size of $\phi_j G$ (as shown in Fig. 5).

Based on these assumptions, we can model the service of either the MeNB or SeNB as an M/G/1 queue with batch arrivals [35]. Specifically, the X2 link delay should be considered for the SeNB, which is denoted as T_{X2}. Then the expected delivery delay experienced by the packets dispatched to the MeNB and SeNB are given by:

$$\begin{aligned} D_1^d =& \frac{\rho_1^d \mathbb{E}[X_1^2]}{2(1-\rho_1^d)\mathbb{E}[X_1]} + \frac{(\phi_1 G-1)\mathbb{E}[X_1]}{2(1-\rho_1^d)} + \mathbb{E}[X_1], \\ D_2^d =& \frac{\rho_2^d \mathbb{E}[X_2^2]}{2(1-\rho_2^d)\mathbb{E}[X_2]} + \frac{(\phi_2 G-1)\mathbb{E}[X_2]}{2(1-\rho_2^d)} + \mathbb{E}[X_2] \\ &+ \frac{T_{X2}}{1-\rho_2^d}, \end{aligned} \tag{3}$$

respectively, where the first term is the mean waiting time in the system when packets arrive one by one with rate $\lambda G\phi_j$, and $\rho_j^d = \lambda G\phi_j \mathbb{E}[X_j]$ is the traffic intensity. The second term is the extra delay of waiting for the service in the batch, and the third term is the service time. The fourth term for the SeNB denotes the X2 link delay.

In order to address the packet out-of-order arrival problem at the UE, the packets should be dispatched such that the delivery delay difference between the MeNB and SeNB should be as small as possible to ensure the minimum delivery delay for each batch. Therefore, we can optimize the split rate of one batch to achieve the minimum delay, which can be

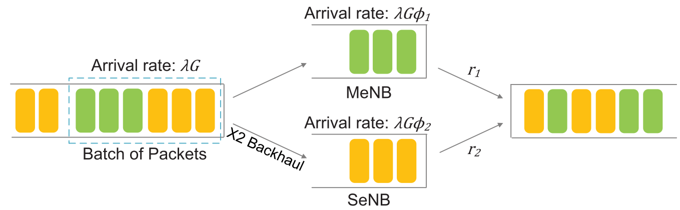


Fig. 5. Queueing models for concurrent transmissions in the conventional DC scheme.

formulated as an optimization problem as follows:

$$\begin{aligned} \min_{\phi_1,\phi_2} \quad & \max\{D_1^d, D_2^d\} \\ s.t. \quad & \phi_1+\phi_2 = 1, \\ & \lambda G\phi_j < \frac{1}{\mathbb{E}[X_j]}, \qquad j=1,2, \\ & \phi_j \geq 0, \qquad j=1,2. \end{aligned} \tag{4}$$

The optimal solution of (4) can be directly obtained under the following conditions, which can therefore achieve the optimal delivery delay for the DC scheme, called the DC scheme with optimal split rate (DC-OS):

1) If $T_{X2} \geq \frac{\lambda G(1-r_2)+Gr_2+r_2-r_1}{2r_1r_2-2\,G\lambda r_2}$, then $\phi_1=1$ and $\phi_2=0$.
2) Else if $T_{X2} \leq \frac{-((G+1)r_1-r_2)+\lambda G(r_1-1)}{2r_1r_2}$, then $\phi_1=0$ and $\phi_2=1$.
3) Else, if $\lambda G < r_1$ and $0 \leq T_{X2} < \frac{\lambda G(1-r_2)+Gr_2+r_2-r_1}{2r_1r_2-2\,G\lambda r_2}$, or if $\lambda G \geq r_1$ and $T_{X2} > 0$, let $D_1^d = D_2^d$, we can obtain:

$$\begin{aligned} \phi_1 =& \frac{((G+1)r_1-r_2)-\lambda G(r_1-1)+2r_1r_2T_{X2}}{\lambda G(2-r_1-r_2)+G(r_1+r_2)+2r_2\lambda GT_{X2}}, \\ \phi_2 =& 1-\phi_1. \end{aligned}$$

C. Queueing Model for RCDC Scheme

In the RCDC scheme, the encoder at the MeNB can generate as many encoded packets as needed from each batch of G source packets, which are then separately transmitted through the MeNB and SeNB respectively. Since we mainly consider the heavy traffic load scenario in the DC network, we can adopt the early encoding in the RCDC scheme so that we can assume that the encoded packets can transmit to the SeNB to compensate the X2 link delay. Let N_G denote the number of encoded packets needed at the UE for successfully recovering the original G packets in one batch, then from UE's perspective, as long as it receives N_G encoded packets from either the MeNB or the SeNB, it can decode the current batch of packets (as shown in Fig. 6). Specifically, $N_G = G(1+\epsilon)$ for raptor codes with $\epsilon > 0$, to ensure $N_G > G$ for the successfully decoding of the UE. Due to the low time complexity for Raptor codes, we assume that the encoding and decoding time is much less than the waiting time for enough encoded packets at the UE before being able to decode the whole batch.

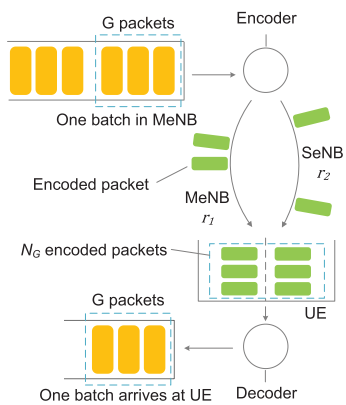


Fig. 6. Queueing models for the RCDC scheme.

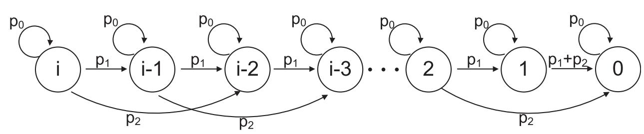


Fig. 7. Markov chain for the reception states of the encoded packets at the UE.

Therefore, in our model, we mainly consider the transmission and queueing time for the whole batch of encoded packets from the MeNB to the UE as the service time.

Following the channel and transmission model introduced in the previous subsection, in each time slot, there are three possible cases for the number of encoded packets received by the UE:

$$\begin{cases} 0 \text{ packet}: & p_0 = (1-r_1)(1-r_2), \\ 1 \text{ packet}: & p_1 = r_1(1-r_2) + r_2(1-r_1), \\ 2 \text{ packets}: & p_2 = r_1 r_2, \end{cases} \tag{5}$$

where p_0, p_1 and p_2 denote the probabilities of receiving 0, 1 and 2 encoded packets in each time slot respectively.

As shown Fig. 7, we can model the reception of the encoded packets at the UE as a markov chain, since the remaining packets needed only depends on the previous value. The state i denotes that i encoded packets are still needed for successful decoding the original packets. Based on (5), we can see that at the end of each time slot, the markov chain will make a transition from state i to states i, $i-1$ and $i-2$ with the probabilities of p_0, p_1 and p_2 respectively. This process is repeated until state 0 is reached, which corresponds to the successful reception of enough encoded packets and being able to recover the original batch.

Let T_i denote the first-passenger time from state i to state 0 as the service time, and $H_i(z)$ denote the generating function of T_i, then we can obtain the following recursive equations for $H_i(z)$ from the markov chain:

$$\begin{cases} H_i(z) = z(p_0 H_i(z) + p_1 H_{i-1}(z) + p_2 H_{i-2}(z)), \quad i \geq 2 \\ H_1(z) = z(p_0 H_1(z) + (p_1+p_2) H_0(z)), \\ H_0(z) = 1. \end{cases} \tag{6}$$

The close-form expression for $H_i(z)$ can be obtained by solving the recursive equations in (6) as follows:

$$\begin{aligned} H_i(z) =& 2^{-1-i}\left[\left(\frac{p_1 z}{1-p_0 z} - A(z)\right)^i \left(1 - \frac{(p_1+2p_2)z}{(1-p_0 z)A(z)}\right)\right. \\ &\left. + \left(\frac{p_1 z}{1-p_0 z} + A(z)\right)^i \left(1 + \frac{(p_1+2p_2)z}{(1-p_0 z)A(z)}\right)\right], \end{aligned} \tag{7}$$

where

$$A(z) = \sqrt{\frac{z(p_1^2 z + 4p_2(1-p_0 z))}{(-1+p_0 z)^2}}.$$

We can obtain the mean service time $\mathbb{E}[T_i]$ from $H_i(z)$ as follows:

$$\mathbb{E}[T_i] = H_i'(1) = \frac{i}{p_1+2p_2} + \frac{p_2\left(1 - \left(-\frac{p_2}{1-p_0}\right)^i\right)}{(p_1+2p_2)^2} \tag{8}$$

Similarly, the second moment of T_i can be given by:

$$\begin{aligned} \mathbb{E}[T_i^2] =& H_i''(1) + H_i'(1) \\ =& \frac{2p_0}{(1-p_0)^2}\left[1 - \frac{p_2 + (1-p_0)\left(-\frac{p_2}{1-p_0}\right)^i}{p_1+2p_2}\right] \\ &+ \frac{i(p_1+2p_2) + p_2\left(1-\left(-\frac{p_2}{1-p_0}\right)^i\right)}{(p_1+2p_2)^2} \\ &+ \sum_{j=2}^{i}\left[-\frac{2p_2}{(1-p_0)(p_1+2p_2)^2}\left(-\frac{p_2}{1-p_0}\right)^j\right. \\ &+ \left(\sum_{n=2}^{j}\left(-\frac{p_2}{1-p_0}\right)^{j-n} \frac{2}{1-p_0}\left(\frac{n}{p_1+2p_2}\right.\right. \\ &\left.\left.\left. + \frac{p_2}{(1-p_0)^2} - 1\right)\right)\right]. \end{aligned} \tag{9}$$

Note that the expected service time for a batch of G packets is corresponding to the time for the UE to receive N_G encoded packets, which equals to $\mathbb{E}[T_{N_G}]$ and can be given by (8) as follows:

$$\mathbb{E}[T_{N_G}] = \frac{N_G}{p_1+2p_2} + \frac{p_2\left[1 - \left(-\frac{p_2}{1-p_0}\right)^{N_G}\right]}{(p_1+2p_2)^2}. \tag{10}$$

Therefore, in the RCDC scheme, the successful transmission of a batch of G source packets is equivalent to the reception of N_G encoded packets, with the first and second moment of the service time given by $\mathbb{E}[T_{N_G}]$ and $\mathbb{E}[T^2_{N_G}]$ respectively. In this way, we can model the RCDC scheme as an M/G/1 queue with the arrival rate of λ, the mean service rate of $1/\mathbb{E}[T_{N_G}]$, and the traffic intensity of $\rho_r = \lambda\mathbb{E}[T_{N_G}]$.

Finally, we can obtain the mean delivery delay for the RCDC scheme following the M/G/1 queueing model as follows:

$$D_r = \frac{\rho_r \mathbb{E}[T^2_{N_G}]}{2(1-\rho_r)\mathbb{E}[T_{N_G}]} + \mathbb{E}[T_{N_G}], \tag{11}$$

where the first term corresponds to the queueing delay and the second term denotes the expected service time for N_G encoded packets.

D. RCDC Scheme With Optimal Sub-Block Size

From equation (11), it can be seen that the delivery delay incurred by the RCDC scheme depends on the batch size, in which the UE needs to wait enough encoded packets for decoding the whole batch of packets and this may incur a large delivery delay especially for the large batch size. To investigate this effect, we propose an enhanced sub-block encoding scheme for the RCDC scheme, in which a batch of the original packets can be divided into multiple sub-blocks (i.e., the batch has only one sub-block represents the RCDC scheme), and the encoding and decoding are performed based on the source packets in each sub-block. Let K denote the sub-block size, thus, for a batch of G original packets, they can be divided into $n = \lceil \frac{G}{K} \rceil$ sub-blocks, where $\lceil \cdot \rceil$ denote the ceiling function. Let N_K denote the number of encoded packets required for successful decoding of the K packets in each sub-block. Therefore, the first and second moment of the service time for one sub-block is given by $\mathbb{E}[T_{N_K}]$ and $\mathbb{E}[T^2_{N_K}]$ respectively.

In this way, we can model the enhanced scheme as an M/G/1 queue with batch arrivals with the arrival rate of λ, the mean service time of $\mathbb{E}[T_{N_K}]$, and the traffic intensity of $\rho_{sub} = \lambda n \mathbb{E}[T_{N_K}]$. Therefore, the mean delivery delay achieved by this scheme is given by:

$$D_{sub} = \frac{\rho_{sub}\mathbb{E}[T^2_{N_K}]}{2(1-\rho_{sub})\mathbb{E}[T_{N_K}]} + \frac{(n-1)\mathbb{E}[T_{N_K}]}{2(1-\rho_{sub})} + \mathbb{E}[T_{N_K}], \tag{12}$$

where the first term is the mean queueing delay in the system for one sub-block, the second term is the extra delay for waiting for the front sub-blocks being served and the last term corresponding to the service time for each sub-block, which can be obtained by substituting T_i for N_K in (8).

In Fig. 8, we show the delay of the sub-block encoding scheme with different sub-block sizes. For each batch size G, the number of encoded packets N_G required for at least 99% of successful decoding is shown in Table II based on RaptorQ specification [32]. It can be seen that the delay firstly reduces with the increase of the sub-block size and then starts to increase gradually. For the quite small sub-block size, the rate of the necessary number of encoded packets for decoding over the original size is much larger. In this case, the decoder needs to receive more encoded packets for one sub-block, which introduces more delay. With different sub-block size, the RaptorQ specification formulates the different required encoded packets, so that the curve is not smooth. For a large sub-block size, the waiting time for decoding increases so that it will spend more time waiting for enough encoded packets. Therefore, for a given batch size, the optimal sub-block size can be found such that the minimum delay can be achieved with a tradeoff between the sub-block size and the delivery time, which is called the RCDC scheme with the optimal sub-block size (RCDC-OB). Therefore, the RCDC-OB scheme can further reduce the delivery delay by adopting the sub-block encoding scheme.

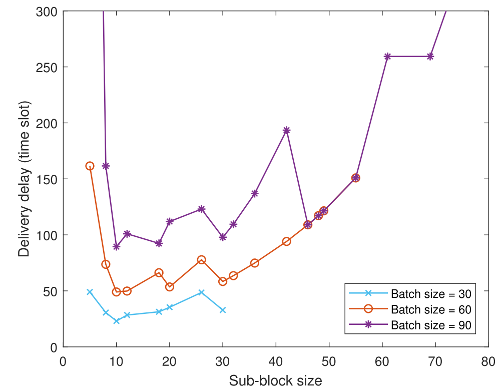


Fig. 8. Average delivery delay with different sub-block size.

TABLE II
CORRESPONDENCE NUMBER BETWEEN ORIGINAL PACKETS AND DECODING PACKETS

Original packets	Required packets
$G \leq 10$	$N_G = 10$
$10 < G \leq 12$	$N_G = 12$
$12 < G \leq 18$	$N_G = 18$
$18 < G \leq 20$	$N_G = 20$
$20 < G \leq 26$	$N_G = 26$
$26 < G \leq 30$	$N_G = 30$
$30 < G \leq 32$	$N_G = 32$
...	...

V. PERFORMANCE EVALUATION

In this section, we firstly compare the performance of the proposed RCDC and RCDC-OB schemes with the DC-OS scheme based on the theoretical results derived in the previous section. We then evaluate the delay performance based on the simulations via NS-3.

A. Numerical Results

In the DC-OS scheme, the overall delay is determined by the larger one of two paths as given by equation (3), and the optimal dispatching ratio can be obtained from (4). Under this condition, the service rates of the MeNB and SeNB, as well as the X2 link delay may affect the delivery delay in different ways. For the RCDC and RCDC-OB schemes, the delay is determined by the overall service rate of the MeNB and

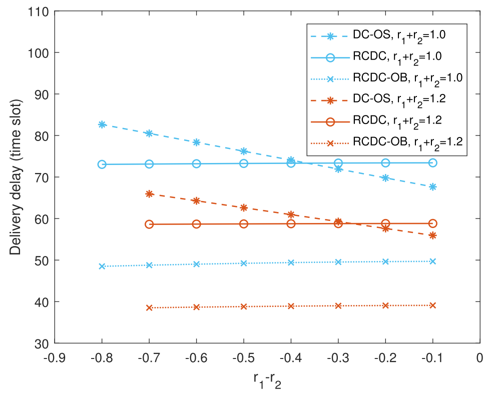


Fig. 9. Average delivery delay under different service rate of eNBs with $\lambda = 0.005$.

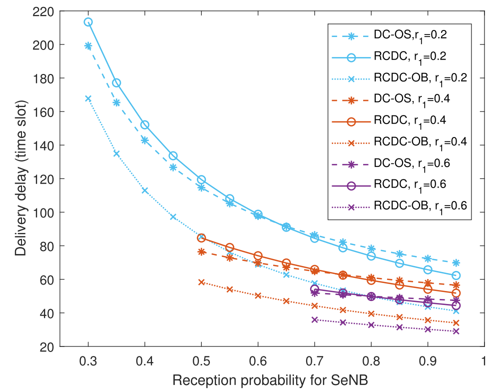


Fig. 10. Average delivery delay under different service rate of eNBs with $\lambda = 0.005$.

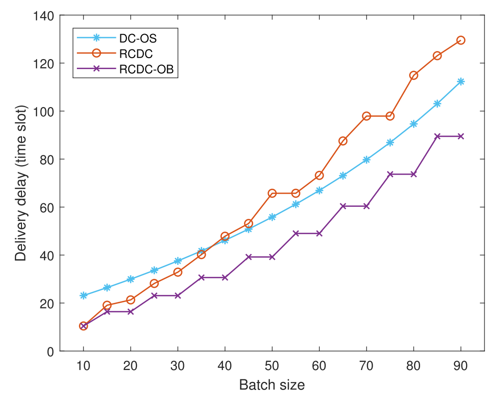


Fig. 11. Average delivery delay under different batch sizes with $\lambda = 0.005$, $r_1 = 0.2$ and $r_2 = 0.8$.

SeNB, so the RCDC schemes can be less affected to the difference of the service rate between two eNBs.

To verify this effect, we present the numerical results to show the average delivery delay under different service rates of the MeNB and SeNB in Fig. 9. We fix the sum service rate of the MeNB and SeNB, and differentiate the service rates of these two eNBs to achieve unbalanced DC link conditions. Normally, the SeNB has better channel condition to UE in the DC network, thus we assume that the UE has the probability for successful reception from the MeNB in each time slot is larger than that from the SeNB. The delay of the DC-OS scheme is given by (4), the network delay of the RCDC scheme is obtained from (11) and (12) for RCDC-OB scheme.

Fig. 9 shows that under the same sum service rate condition (e.g., $r_1 + r_2 = 1.0$ or 1.2 respectively), the delay performance achieved by the RCDC scheme and RCDC-OB schemes are at the similar level regardless the service rate difference between the MeNB and SeNB, which demonstrates that the RCDC and RCDC-OB schemes can achieve a stable service and provide the robustness of the transmission. On the contrary, for the DC-OS scheme, the mean delivery delay decreases gradually with the increase of the service rate of the MeNB, which can mitigate the influence from the X2 backhaul delay to the SeNB. The delay performance of the DC-OS scheme can even be better than the RCDC scheme when the differences of two service rates become small, since the MeNB can serve more packets with a high service rate. In this case, the impact of the X2 link delay for DC-OS is much smaller than the impact of the waiting time for enough packets in the RCDC scheme. It also can be seen that for a larger sum service rate, the X2 link delay has more impact on the delivery delay achieved by the DC-OS scheme. The RCDC-OB achieves the best performance under different conditions which shows that the scheme has fewer effects on the waiting time for decoding the whole batch.

In addition, we present the numerical results to show the average delivery delay by fixing the service rate of the MeNB and increasing the service rate of the SeNB. From Fig. 10, it can be seen that the mean delivery delays of all three schemes can be reduced if the service rate of the SeNB increases given different service rate of the MeNB (e.g., $r_1 = 0.2, 0.4$ or 0.6 respectively). When the service rate of the SeNB is low, the RCDC scheme has a relatively worse performance which shows the impact from the whole waiting time for receiving enough encoded packets. Nevertheless, the RCDC scheme outperforms the DC-OS scheme with a high service rate of the SeNB since the delivery time may become short and the waiting time for enough packets is not the dominant part. By using the sub-block encoding scheme, the RCDC-OB has better results under all conditions.

Finally, we provide the numerical results for the delivery delay achieved by three different schemes under different batch size condition. As shown in Fig. 11, we can firstly notice that the delay experienced by all three schemes increase gradually with the batch size. For the DC-OS scheme, this is due to the increase of the traffic intensity and the queueing delay in the batch due to the larger batch size. For the RCDC and RCDC-OB schemes, it is mainly because the number of encoded packets required to decode the original packets is increased with the batch size. It can be seen that the RCDC scheme is effective in reducing the delay comparing with the DC-OS scheme under the small batch size conditions since the link utilization of the SeNB can be improved due to the early encoding method. However, if the batch size is increased beyond certain region (about 40 packets in this case), the performance gap between the DC-OS and RCDC schemes are diminishing, and the delay achieved by the RCDC scheme can

TABLE III
MAIN SIMULATION PARAMETERS

Parameters	Value
MeNB carrier frequency	2.1 GHz
MeNB transmit power	30 dBm
MeNB bandwidth	20 MHz
SeNB carrier frequency	10 GHz
SeNB transmit power	30 dBm
SeNB bandwidth	100 MHz
Arrival rate of Poisson process	{0.02, 0.033 (default)} /ms
Distance between eNBs and UE	100 m (default)
X2 link delay	{0.1, 0.5, 1 (default), 5, 10} ms
Batch size	100 packets (default)

be even larger than that of the DC-OS scheme, which is undesirable since the waiting time for successful decoding a whole batch of packets becomes the dominant part and the impact of the X2 link delay in DC-OS scheme decreases. In addition, the delay achieved by the RCDC-OB scheme is always better than the DC-OS scheme, even under the large batch size conditions, which represents that the RCDC-OB scheme can effectively reduce the waiting delay for enough packets by adopting the sub-block encoding scheme.

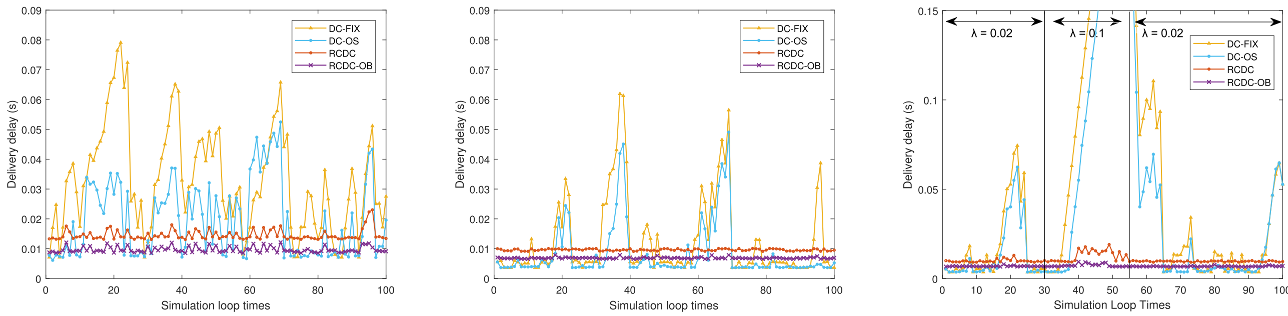
B. Simulation Results

The numerical results have shown the mean delivery delay achieved by the proposed scheme. In order to evaluate the instantaneous delay performance for each batch under a dynamic network condition, we implement the proposed RCDC and RCDC-OB schemes, as well as the conventional DC scheme using the NS-3 network simulator. We extend the dual connectivity module from [36] and considering the pathloss and the shadowing effects in our simulations. We consider the scenario that one MeNB and one SeNB are connected through a X2 backhaul link, and one UE can receive the data from both two eNBs. The traffic arrivals follow the Poisson process and the main parameters of the simulations are given in Table III.

In the simulation, we introduce four schemes for comparisons, namely DC-FIX, DC-OS, RCDC, and RCDC-OB. DC-FIX is regarded as a benchmark in the DC network with the split rate of 0.5 which will not be changed under all conditions. DC-OS is the scheme we have introduced in Section IV-B and the split rate for one batch can be automatically adjusted following the transmission conditions and the link state. To deal with the out-of-order arrival problem in the DC-FIX and DC-OS schemes, we assume that the packet is successfully received by the UE only if all previous packets in the batch are received. The RCDC scheme is the fundamental Raptor codes based dual connectivity scheme and the RCDC-OB scheme considers the optimal sub-block size.

In Fig. 12, we show the instantaneous delivery delay in three different scenarios. Fig. 12(a) represents a high traffic intensity with a larger X2 link delay between the MeNB and the SeNB, Fig. 12(b) shows a low traffic intensity for the network and Fig. 12(c) shows the scenario with a bursty heavy traffic load. It can be seen that the delay varies significantly using the DC-FIX and DC-OS schemes in both two scenarios. This demonstrates that the traffic load of the MeNB and SeNB cannot be effectively balanced due to the dynamic network conditions, and thus may lead to the out-of-order problem and deteriorates delay performance. DC-OS scheme has a better performance than the DC-FIX scheme. In some cases, the DC-OS scheme can even achieve the lower delay which indicates that under the better channel conditions, the DC-OS scheme can directly transmit the packets to the UE while the RCDC schemes have the process of encoding and decoding. However, the DC-OS still has some large variance from some short-term high-intensity traffic flows, which indicates the dynamic split control mechanism for the batch of packets is not accurate enough under a dynamic channel and traffic condition. In Fig. 12(a), the delay performance is improved using the RCDC and RCDC-OB scheme with a smaller variation, and the average delay is also much lower than the conventional DC schemes. This can demonstrate that the RCDC schemes can outperform in heavy traffic load condition compared with conventional DC schemes. It also shows that the RCDC-OB scheme achieves better performance than the RCDC scheme by encoding the packets in smaller sub-block sizes, which reduces the waiting time for the whole batch of packets. However, in Fig. 12(b), we can also notice that when the traffic load is low, although the DC-OS scheme has a large variation, the delivery delay of most batches are smaller than that for the RCDC scheme, which shows that the RCDC scheme is not quite suitable for a low traffic load condition due to a long waiting time for enough packets to decode. The RCDC-OB scheme performs better than the RCDC scheme using the sub-block encoding scheme to reduce the waiting time for enough packets which achieves a lower delivery delay. In Fig. 12(c), we set an interval with the scenario of bursty event, in which the arrival rate λ is equal to 0.1, and λ is equal to 0.02 for other time. From the figure, we can see that in a bursty heavy traffic condition, the conventional DC-FIX and DC-OS schemes may have some accumulated delays since the subsequent batch needs to wait for the successful transmission of previous batches. However, the traffic load of the MeNB and SeNB cannot be effectively and quickly balanced in conventional DC schemes under the bursty traffic due to the variable channel conditions. On the other hand, it can be seen that the RCDC and RCDC-OB schemes achieve a better performance in such traffic conditions, where the RCDC-OB scheme has a lower delivery delay. Although the RCDC-OB scheme has a slight variance during the bursty traffic, it will not bring a large delivery delay which verifies the robustness of the proposed scheme.

In Fig. 13, we show the average delivery delay and the standard deviation achieved by these schemes under different X2 link delay conditions (with delays in {0.1, 0.5, 1, 5, 10} ms [37]). As seen from the figure, when the X2 link delay is small, the average delay as well as the standard deviation achieved by these four schemes are similar, which indicates the lower X2 link delay has less contribution for the whole transmission delay. Furthermore, we can see that the DC-OS scheme has a better performance than the RCDC scheme since the RCDC scheme needs to wait for enough encoded packets for recovering the original batch of packets. When the X2 link



(a) Arrival rate of Poisson process 0.033, X2 link delay 5ms (b) Arrival rate of Poisson process 0.02, X2 link delay 1ms (c) Variable arrival rate of Poisson process 0.02 and 0.1, X2 link delay 1ms

Fig. 12. Instantaneous delivery delay with different schemes.

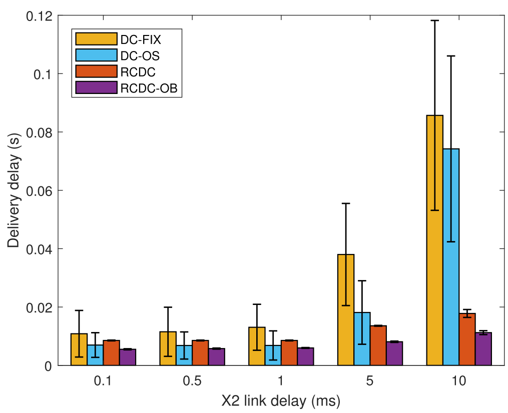


Fig. 13. Average delivery delay and standard deviation under different X2 link latency.

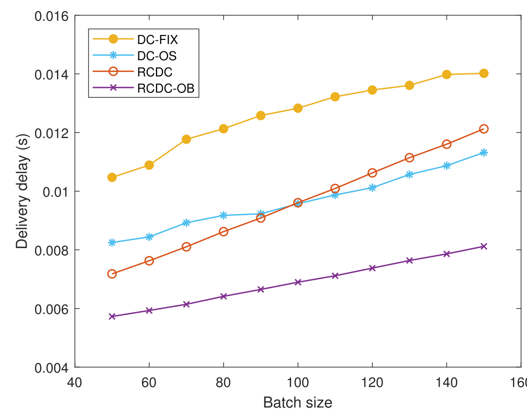
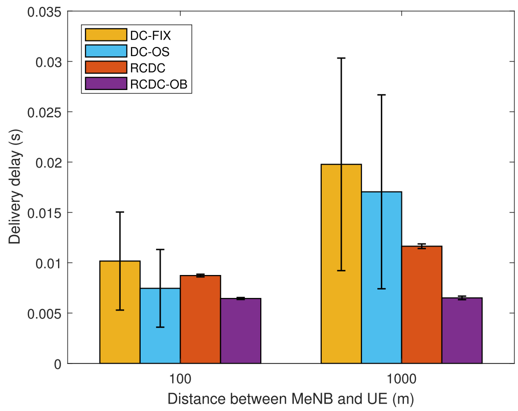


Fig. 14. Average delivery delay with different batch size.

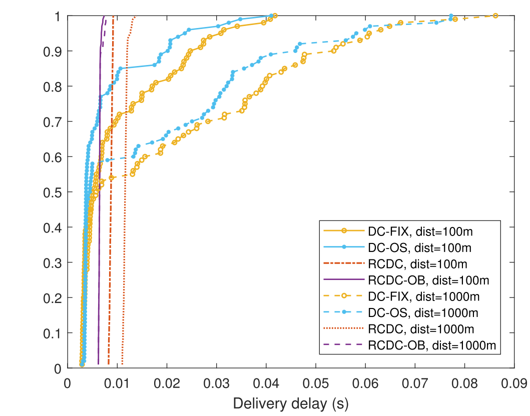
delay increases, the average delivery delay as well as the standard deviation achieved by these four schemes increase accordingly. With a high X2 link delay, the performance of the DC-FIX and DC-OS schemes are significantly affected by the X2 link delay during the transmission, while the RCDC and RCDC-OB schemes are much less affected. Among these schemes, the RCDC-OB scheme achieves the best performance in terms of the delay variation and outperforms the other two schemes with respect to the average delivery delay.

In Fig. 14, we show the average delivery delay with different batch sizes. The DC-FIX scheme has always the highest delay under all conditions, which indicates that the fixed split rate brings the overloaded or underflow problems in the SeNB which cannot adapt the dynamic network condition. Similar to the results in Fig. 11, the RCDC scheme is better than the DC-OS scheme for small batch sizes. However, if the batch size is too large, it takes a longer time for the UE to receive enough encoded packets to decode the original packets. As a result, the delay incurred by the RCDC scheme under the large batch size regime becomes larger than that of the DC-OS scheme. It also can be seen that by using the sub-block encoding scheme, the RCDC-OB scheme achieves the best performance under all conditions.

Finally, we investigate the effect of channel conditions on the delay performance shown in Fig. 15, especially considering the pathloss effects. In this simulation, we fix the distance between the SeNB and UE to be 100 meters and consider two distance settings between the MeNB and UE, namely 100 meters and 1000 meters, which represents two different link states of the DC network respectively. As shown in Fig. 15(a), the average delivery delays achieved by the DC-FIX scheme always causes a large delay compared with other schemes. The DC-OS scheme performs better than the RCDC scheme in a short distance scenario with the optimal split rate. However, the DC-OS scheme in the large distance scenario is larger than that in the short distance scenario, and the variation is also more significant while the RCDC scheme achieves a small variation under two scenarios. The RCDC-OB scheme has a quite similar performance under both scenarios in delivery delay and a small increment of the variation. In addition, the cumulative distribution functions in delivery delay for different schemes are shown in Fig. 15(b). In some cases, the DC-FIX and DC-OS schemes can have a lower delivery delay which indicates that the conventional DC schemes can achieve a lower delay under the better channel conditions (e.g., the distance between the MeNB and UE is small), even better than our proposed RCDC scheme that requires extra time for waiting the enough packets for whole batch. However, when the distance between the MeNB and UE is large, i.e., the channel condition becomes worse, the DC-OS scheme cannot accurately control the split rate, so that the delay is distributed in a wide range, while the RCDC-OB can achieve a relatively low and stable delay in both distance setting.



(a) Average delivery delay and standard deviation



(b) Cumulative Distribution Function

Fig. 15. Delivery delay with different distance between UE and MeNB.

VI. Conclusion

In this paper, we have proposed the RCDC scheme for the DC network to simplify the transmission management for DC network and to address the out-of-order packet delivery problem caused by the non-ideal X2 backhaul and dynamic link conditions between the eNBs and UE. The early encoding method is proposed for a dedicated RCDC layer to improve the link utilization of the SeNB, and thus the extra delay caused by the non-ideal backhaul link can be mitigated, especially when the data load is high. We have developed mathematical models for analyzing the delivery delay performance of the RCDC scheme as well as the DC-OS scheme, and proposed an enhanced RCDC-OB scheme to reduce the delivery delay. Extensive simulations have been conducted to demonstrate that the proposed schemes achieve better performances than the conventional DC scheme under different network conditions. In the future, the proposed method can be utilized in multiple-channel networks, especially in the mobile condition, such as vehicular networking with multiple data pipes, to reach the optimal delivery delay.

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