Low-Latency Routing Scheme for a Fronthaul Bridged Network

Article *in* Journal of Optical Communications and Networking · January 2018

DOI: 10.1364/JOCN.10.000014

Low-Latency Routing Scheme for a Fronthaul Bridged Network

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***Abstract*—A fronthaul bridged network has attracted attention as a means of efficiently constructing the centralized radio access network (C-RAN) architecture. If we change the functional split of C-RAN and employ time-division duplex (TDD), the data rate in fronthaul will become variable, and the global synchronization of fronthaul streams will occur. This feature results in an increase in the queuing delay in fronthaul bridges among fronthaul flows. To address this problem, this paper proposes a novel low-latency routing scheme designed to minimize the worst-case delay in fronthaul networks with path-control protocols. The proposed scheme formulates the worst-case delay of each fronthaul stream based on the distribution of nodes, the propagation delay, and metric of the links. It selects the set of paths that minimizes the maximum value of the worst-case delay from the candidate path sets for fronthaul flows generated with the *k*-th shortest path algorithm. We confirmed with computer simulations that the proposed scheme can adequately minimize the worst-case delay, irrespective of the network topology. The maximum queuing delay is minimized by considering the time synchronization between fronthaul flows and the burst size determined by the TDD subframe length.**

***Index Terms*—Fronthaul bridged network; Low latency; Mobile fronthaul; Routing.**

I. Introduction

Wireless access services have expanded rapidly, and mobile traffic is increasing exponentially [1]. Network capacity can be enhanced by deploying many small cells because cell size reduction results in an increase in spectrum efficiency [2]. In the centralized radio access network (C-RAN) architecture, base station (BS) functions are divided into two building blocks. A fronthaul link is a transport link between them, namely, a distributed unit (DU) and a central unit (CU) [3]. The CU provides baseband signal processing functions, and the DU provides the radio frequency (RF) signal transmission and reception functions. The C-RAN architecture for LTE-A enables BSs to be deployed flexibly and cost-effectively and is capable of performance enhancement through the use of coordinated multipoint transmission and reception (CoMP) [4]. The in-phase and quadrature (IQ) samples of the baseband signals are transmitted in the fronthaul across a common public radio interface (CPRI). To reduce the amount of data transmitted via the fronthaul, it was proposed that the functional split between a DU and a CU be changed [5,6]. Unlike the fixed and large link capacity of CPRI, the data rate in fronthaul is variable and is proportional to the wireless link data rate. Furthermore, the use of time-division duplex (TDD) is considered in C-RAN [7]. In TDD systems, uplink and downlink transmissions occur based on time synchronization between neighboring DUs.

Manuscript received October 6, 2017; revised October 27, 2017; accepted October 30, 2017; published December 22, 2017 (Doc. ID 308589).

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https://doi.org/10.1364/JOCN.10.000014

It has been a significant research topic to efficiently construct fronthaul. To develop an integrated backhaul and fronthaul transport network, a fronthaul network architecture referred to as the Xhaul network has been proposed [8,9]. It consists of high-capacity switches and heterogeneous transmission links to enable flexible and software-defined reconfiguration. Among them, to efficiently construct a fronthaul network, time-sensitive networks for fronthaul is being standardized in IEEE 802.1CM [10]. Fronthaul streams between DUs and CUs are transported via a fronthaul bridged network, which consists of inexpensive layer-2 switches, as shown in Fig. 1. To meet the strict service requirements, the use of time-sensitive networking (TSN) features is considered. In this paper we focus on the end-to-end (e2e) latency requirements for fronthaul streams. To meet the latency target, fronthaul streams are treated as express class, and frame preemption [11,12] can be employed to reduce the effects of other traffic. If an express frame arrives, the transmission of a non-time-critical frame is suspended, and the express frame is immediately transmitted. When the express frames have been transmitted, the transmission of the preempted frame is resumed. In this procedure, the express frame can wait until the transmitted data size of a non-express frame reaches the minimum size for preemption (64 bytes).

To reduce the e2e delay in a fronthaul bridged network, a major challenge is the increasing queuing delay. Figure 2 shows the components of e2e delay in layer-2 networks [13]: the propagation delay, the packet processing delay, the serialization delay, and the queuing delay. The delay variation is mainly caused by the queuing delay; although express flows are usually transmitted in precedence to delay-tolerant flows, queuing delay occurs among flows with the same priority. In particular, bridges periodically receive globally synchronized bursts of fronthaul streams in TDD systems. This is because neighboring DUs simultaneously forward and receive traffic to and from CUs.

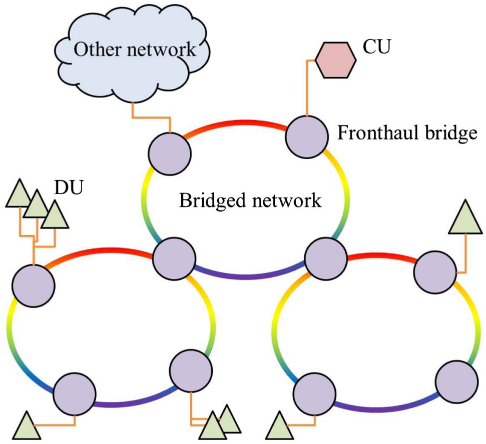

Fig. 1. Fronthaul bridged network.

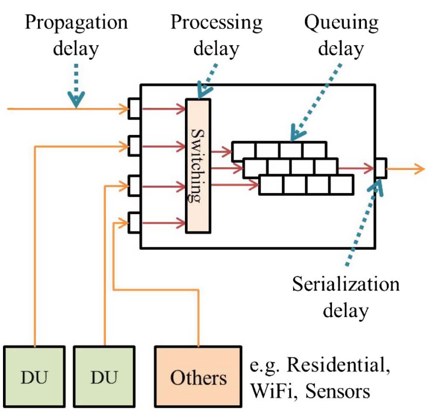

Fig. 2. Components of e2e delay.

The queuing delay among fronthaul flows is increased by this feature of fronthaul networks. Thus, it is critical to reduce the queuing delay to efficiently accommodate fronthaul streams in a bridged network.

For flexibly constructing a bridged network, there are path-control protocols such as 802.1Qca [14], which extend the intermediate system to intermediate system (IS-IS) application and this constitutes TSN. 802.1Qca provides explicit path-control enabling the use of non-shortest paths. An explicit tree (ET) is controlled by a path computation element (PCE) via IS-IS. An algorithm for path computation, which is not specified in the standard, is essential in order to satisfy the latency requirements in a fronthaul network. However, existing quality-of-service (QoS) aware routing schemes cannot be employed for fronthaul networks because they do not consider the frame-level queuing delay caused by globally synchronized fronthaul flows with TDD.

Therefore, this paper proposes a novel low-latency routing scheme to minimize the worst-case delay in fronthaul networks with path-control protocols. The proposed method can efficiently find adequate paths from the defined nonlinear problem, irrespective of the network topology and DU distribution. The basic idea was introduced in [15]. In this paper we propose the revised version of the formulation and the routing algorithm and provide simulation results in typical topologies for wide-area network. The rest of the paper is organized as follows. Work related to QoS routing is summarized in Section II. Section III introduces the proposed scheme. Section IV describes a performance evaluation of the proposed routing approach using simulation results. The conclusion is provided in Section V.

II. Related Work

QoS routing is a well-studied and characterized problem that concerns various network metrics, including cost, capacity, delay, and jitter. QoS routing selects paths that satisfy a set of QoS constraints, while also improving the overall efficiency of network resources. The basic concept behind QoS routing is path selection for traffic requiring bandwidth and e2e delay guarantees [16]. It was shown that a path that satisfies bandwidth, delay, and jitter requirements can be found by using a modified version of the Bellman–Ford shortest path algorithm. The concepts behind an exact QoS routing algorithm are explained in [17], and an exact QoS algorithm SAMCRA was proposed based on an analysis of fundamental elements of multiconstrained routing algorithms. QoS routing algorithms for networks with inaccurate parameters were developed [18,19]. Even if the information available for making routing decisions is uncertain, tractable solutions can be established by decomposing the e2e constraint into local delay constraints. Many restricted shortest path and multiconstrained path algorithms have been developed to select a path that satisfies a set of QoS constraints [20].

The recent research trend in QoS routing involves various wireless networks. QoS aware routing for wireless multimedia sensor networks (WMSn), which support a large number of both non-real-time and real-time multimedia applications, have been developed [21]. The main challenge for this type of routing is to satisfy the requirements imposed by resource-constrained sensor network environments. For cognitive radio networks (CRNs), multihop secondary networks have gained attention, and the routing metric used to select the best route is one of the main features of routing protocols [22]. With the growing requirement of QoS in terms of delay in mobile ad hoc networks (MANETs), an interference-based topology control algorithm was proposed that takes both delay and interference into account [23]. The transmission delay, contention delay, and queuing delay are considered in the proposed algorithm. For industrial wireless sensor networks, a gradient routing with two-hop information was proposed to enhance real-time performance with energy efficiency [24].

To reduce the significant information loss in the process of topology aggregation for large-scale networks, a way of representing the aggregated state in delay-bandwidth-sensitive networks was proposed [25]. The proposed scheme introduced an aggregation algorithm and a corresponding routing protocol using the QoS parameter representation, which accurately captures the network state information. It is thought that topology aggregation is not required for a fronthaul network because the scale of a fronthaul network is limited, and topology aggregation is used for large networks to deal with the scalability problem of routing algorithms.

The e2e latency of a fronthaul network consists of propagation delay, processing delay, serialization delay, and queuing delay [13]. Propagation delay is the delay needed when transmitting data over optical fiber links. Processing delay is the delay that occurs when a node processes a frame and includes address look-up delay and forward error correction (FEC) delay. Serialization delay is the time needed to put all bits of a frame on a physical link. This is the size of the frame divided by the wire rate of the interface because a data frame can be sent onto the link at the serialization rate of the interface. Queuing delay is the time spent waiting for other frames before a frame is forwarded on the link.

In TDD systems, many DUs simultaneously forward and receive traffic to and from CUs. Bridges periodically receive globally synchronized bursts of fronthaul streams. This feature results in an increase in queuing delay among fronthaul flows that are equally prioritized. Although a low-latency scheduling scheme was proposed in [26], it only adjusts the dequeue order on the determined forwarding path. To effectively reduce the queuing delay, a low-latency routing approach is required. However, many traditional QoS routing algorithms consider only propagation delay and bridge delay, including processing delay and serialization delay. As long as the link bandwidth is sufficient, existing routing schemes have not needed to consider the queuing delay because the granularity of the delay requirement is much larger in traditional networks than in fronthaul networks. Moreover, it is difficult to calculate queuing delay in general networks where bridges continuously receive many flows. Thus, a novel low-latency routing scheme is required for fronthaul networks.

III. Proposed Low-Latency Routing

A. Concept

1) Network and Bridge Architecture: First, in this paper we assume the use of path-control protocols in a fronthaul network of TDD-based C-RAN. The functional block of a bridge is depicted in Fig. 3. Frames are forwarded by cut-through switching to reduce processing delay. Incoming traffic is enqueued into the per-flow class queue. The express (class 0) traffic consists of fronthaul flows. Fronthaul flows are enqueued into the class queue with round-robin (RR) and strict priority (SP) schedulers. Then, they are immediately forwarded to the egress port using the frame preemption [11,12] of lower priority frames. The preempted frames are reassembled at the next hop. Considering the worst-case delay, we can assume that a fronthaul stream is always delayed by a 124 byte frame, which is the maximum size of an un-preemptable frame.

2) Overview: The purpose of the proposed routing scheme is to reduce the worst-case e2e delay of all fronthaul flows. For that goal, we formulate the worst-case

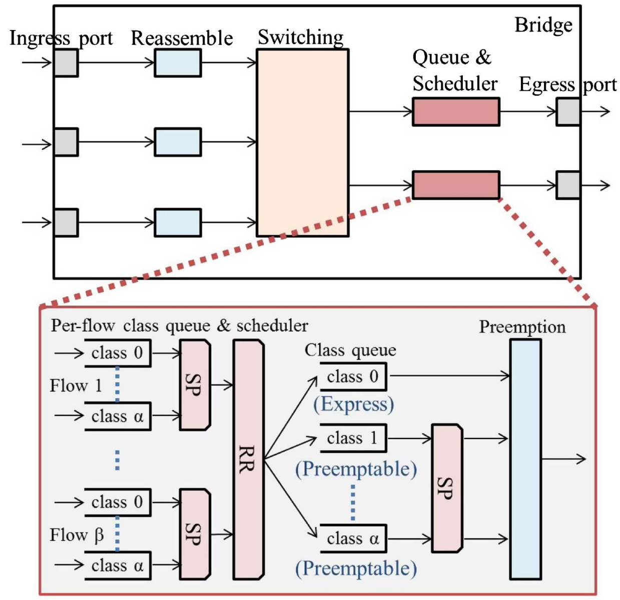

Fig. 3. Functional block of fronthaul bridge.

e2e delay of each fronthaul stream. This formulation is based on the time synchronization between fronthaul flows and the burst size determined by the TDD subframe length. The delay formulation is described in detail in Subsection III.C.

Before the route computation, a PCE collects the required information using IS-IS, such as the distribution of DUs and CUs, the topology of the fronthaul network, and the propagation delay and metric of the links. The PCE generates a set of candidate paths for each fronthaul flow with the k-th shortest path algorithm. Then, it searches the set of paths that minimize the maximum value of the worst-case e2e delay in the network with the Markov chain Monte Carlo (MCMC) method. By setting the delay threshold of fronthaul streams, the proposed routing scheme can judge whether or not the delay requirements are satisfied for all streams. Fronthaul flows are forwarded using the calculated paths until the route computation is executed again; the route calculation is only executed when the flow distribution changes, e.g., a new DU is connected to the network.

B. Variables

Variables used in the formulation of the proposed scheme are shown in Table I. Let $G = (V, E)$ denote a directed graph that represents a fronthaul network, where V is a set of nodes and E is a set of links. For formulation purposes, E includes all fronthaul bridges and DUs and CUs connected to the bridged network, which means all the nodes shown in Fig. 1. V consists not only of links between fronthaul bridges but also of DU-bridge links and CU-bridge links. Because of the definition of e2e delay between DUs and CUs, the processing delay of the DUs and CUs is not considered. We assume that the link bandwidths

TABLE I
VARIABLES AND PARAMETERS

Variable	Definition
F	Set of fronthaul flows in fronthaul network
f	Flow identifier, $f \in F$
P_f	Set of candidate paths for $f \in F$
p	Path identifier, $p \in P_f$
k_f	Maximum size of P_f decided by operator
$N_{f,p}$	Set of nodes on $p \in P_f$ for $f \in F$, $N_{f,p} \subset V$
n	Node identifier, $n \in N_{f,p}$
$L_{f,p}$	Set of links on $p \in P_f$ for $f \in F$, $L_{f,p} \subset E$
l	Link identifier, $l \in L_{f,p}$
e_l	Capacity of l
$\lambda_{f,l}$	Maximum competition number for l
F_l	Set of flows that traverse l, $F_l \subset F$
m	Maximum burst size in fronthaul network
$d^{\mathrm{e2e}}_{f,p}$	e2e delay for p-path of f-th flow
d^{prc}_n	Processing delay of n-th node
d^{prop}_l	Propagation delay of l-th link
d^{ser}_l	Serialization delay of l-th link
$d^q_{f,l}$	Queuing delay of l-th link
τ	Threshold for worst-case delay in fronthaul network
$x_{f,p}$	Selection state of p-th path of f-th flow
$\mathcal{S}$	State of path selection

between fronthaul bridges are the same. A high-speed link is considered to be multiple links in proportion to the link speed to simplify the formulation.

Let $\#(A)$ denote the number of elements in a set A. Let $\max(a,b)$ and $\min(a,b)$ denote the larger and smaller values of a and b, respectively.

C. Delay Formulation

The worst-case e2e delay of each flow is calculated in the proposed scheme to compute the optimal route.

1) e2e Delay: The e2e delay for the p-th path of the f-th flow in a fronthaul network is denoted as $d^{\mathrm{e2e}}_{f,p}$ and formulated as

$$d^{\mathrm{e2e}}_{f,p} = \sum_n d^{\mathrm{prc}}_n + \sum_l d^{\mathrm{prop}}_l + \sum_l d^{\mathrm{ser}}_l + \sum_l d^q_{f,l}, \tag{1}$$

which is the total processing delay, propagation delay, serialization delay, and queuing delay of the forwarding path. These variables are depicted in Fig. 4. Processing delay d^{prc}_n is treated as a fixed value required to forward a frame, which is determined by the processing speed of the bridge. Propagation delay d^{prop}_l is a symmetric and static value determined by the fiber length. Serialization delay d^{ser}_l is proportional to the frame size and is inversely proportional to the link capacity. Queuing delay $d^q_{f,l}$ is caused by the competition among fronthaul streams, i.e., a bridge receives multiple flows at the same time, and they are forwarded in sequence. When fronthaul flows are time-synchronized forwarded in TDD systems, $d^{\mathrm{e2e}}_{f,p}$ increases with the increase in $d^q_{f,l}$. In the next section, we formulate the worst-case queuing delay of the l-th link.

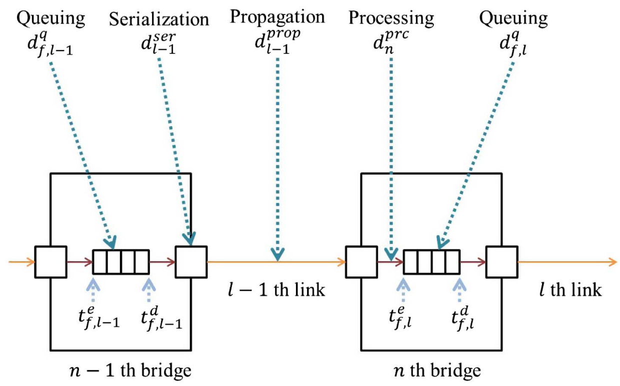

Fig. 4. Enqueue and dequeue time.

2) Queuing Delay: When the f-th flow races against the g-th flow at the l-th link, they are defined as competitive. The g-th flow is a competitive flow for the f-th flow. This competition can cause the f-th flow to wait for the transmission of the g-th flow. The worst-case delay is $\frac{m}{e_l}$, where m denotes the maximum burst size in a fronthaul network and e_l denotes the link capacity. Queuing delay increases in proportion to the number of competitive flows at the l-th link. The maximum queuing delay of the l-th link is formulated as

$$d^{Q\,\max}_{f,l} = \frac{m\lambda_{f,l}}{e_l}, \tag{2}$$

where $\lambda_{f,l}$ denotes the maximum number of competition for the f-th flow at the l-th link.

Note that delays are computed with the assumption that all streams send the maximum size of burst data because the goal of the proposed scheme is to minimize the worst-case e2e delay among fronthaul streams. Thus, it is needless to consider traffic variations in this equation. Although Eq. (2) is not satisfied when the data rate changes from the maximum bursts, this is not a problem because, in this case, the e2e delay is reduced from the worst case. For the same reason, the route calculation is performed only if the network topology including the distribution of DUs and CUs is changed.

3) Number of Flows in Queue: Let F_l denote the set of flows that traverse the l-th link. F_l is computed based on the forwarding path of each flow. The maximum number of competition $\lambda_{f,l}$ is calculated as the number of flows, which are enqueued with the f-th flow at the same time. This value is calculated from F_l based on the enqueue and dequeue time of each flow.

Let $t^e_{f,l}$ and $t^d_{f,l}$ denote the enqueue and dequeue time of the f-th flow at the l-th link, respectively. $t^e_{f,l}$ is calculated as the total of the dequeue time of the $l-1$-th link, the serialization and propagation delay of the $l-1$-th link, and the processing delay of the n-th node. The queuing delay of the l-th link is equal to the difference between $t^e_{f,l}$ and $t^d_{f,l}$. This is calculated with Eq. (2), where $\lambda_{f,l}$ is determined as the number of flows in the queue at $t^e_{f,l}$. Thus, $t^e_{f,l}$ and $t^d_{f,l}$ are formulated as

$$t_{f,l}^{e} = t_{f,l-1}^{d} + d_{l-1}^{\mathrm{ser}} + d_{l-1}^{\mathrm{prop}} + d_{n}^{\mathrm{prc}}, \tag{3}$$

$$t_{f,l}^{d} = t_{f,l}^{e} + \frac{m\lambda_{f,l}}{e_l}. \tag{4}$$

Using Eqs. (3) and (4), $t_{f,l}^{e}$, $t_{f,l}^{d}$, and $\lambda_{f,l}$ can be calculated recursively.

4) Worst-Case e2e Delay: Let $d_{f,p}^{\mathrm{Max}}$ denote the worst-case e2e delay for the p-th path of the f-th flow in a fronthaul network. Based on Eq. (1), it is formulated as

$$d_{f,p}^{\mathrm{Max}} = \sum_{n} d_{n}^{\mathrm{prc}} + \sum_{l} d_{l}^{\mathrm{prop}} + \sum_{l} d_{l}^{\mathrm{ser}} + \sum_{l} d_{l}^{Q\ \mathrm{max}}. \tag{5}$$

The requirement for a fronthaul network is

$$d_{f,p}^{\mathrm{Max}} \le \tau \quad \forall f, \tag{6}$$

where the worst-case e2e delay does not exceed the threshold.

D. Routing Algorithm

This section describes the proposed routing algorithm based on the delay formulation. To describe the algorithm, we introduce a binary function $x_{f,p}$ that denotes the selection state of the p-th path of the f-th flow. $x_{f,p} = 1$ means that the p-th path is selected, and $x_{f,p} = 0$ means that it is not selected.

1) Path-Set Generation: Before the routing procedure, the PCE generates a set of candidate paths P_f for each flow. Let k_f denote the maximum size of P_f, and we assume it is set by the network operator. The PCE finds the *1*-st to k_f-th shortest path of each flow and inserts them into P_f, using the k-shortest path algorithm. If k_f is not restricted, the k-shortest path algorithm finds all possible paths. Consequently, P_f is generated for each flow.

The calculation of the shortest path is based on the link metric information collected with the routing protocol. The metric for each link is set by the network operator. It is reasonable to set the link metric in proportion to the propagation delay of the link, but the policy for deciding the link metric is not limited to this.

2) Formulation for Path Selection: The PCE selects a path from the generated path set for each flow. The purpose of path selection is to find the best path sets to minimize the maximum value of the worst-case e2e delay in the network. The mathematical description of the above requirement is

$$\text{Min } \max(d_{f,p}^{\mathrm{Max}}), \tag{7}$$

$$\text{s.t.}, \sum_{p} x_{f,p} = 1, \quad \forall f,$$

$$x_{f,p} \in \{0, 1\}. \tag{8}$$

The objective is to find the optimal paths to minimize the maximum value of $d_{f,p}^{\mathrm{Max}}$, which is formulated in Eq. (7). The constraint is that one path is selected from the path-set for each flow [shown in Eq. (8)].

Then, the proposed scheme judges whether the delay requirements are satisfied or not with

$$d_{f,p}^{\mathrm{Max}} x_{f,p} \le \tau, \quad \forall f, \tag{9}$$

where $d_{f,p}^{\mathrm{Max}}$, which is calculated with the formulation in Subsection III.C of the selected path, does not exceed the threshold in the fronthaul network for all the flows.

3) MCMC Method: This paper employs the MCMC approach to select the optimum paths. MCMC is a computer-driven sampling method to randomly draw samples from stationary distributions. It finds the optimum solution based on random walk on a Markov chain model. This approach is reasonable because the MCMC method can efficiently find the optimum solution by searching the neighbor of the shortest paths. In other words, the optimum solution is expected to be the neighbor of the shortest paths; many flows are forwarded along their shortest paths, and some flows are assigned to their roundabout paths.

To this end, we formulate the path-selection process as a Markov chain model, in which the path-reselection is described as a transition between the states. We define $\mathcal{S} = \{x_{0,0}, x_{0,1}, \ldots, x_{\#(F),0}, \ldots\}$ as a state of a Markov chain. $\mathcal{S}$ denotes a state of path-selection, whether each candidate path is selected or not selected. Based on the defined Markov chain model, the path-reselection is described as a transition between the states. The set-of-state $\mathcal{M} = \{\mathcal{S}_0, \mathcal{S}_1, \ldots\}$ is generated by searching all possible states. Then, the Markov state transition matrix is generated, assuming that the transition probabilities between states are equally allocated.

The sequence of the proposed method is as follows. First, when an initial condition for the network topology and distribution of DUs and CUs is given, the initial paths are selected using the shortest path algorithm. The competitive flows are counted based on the selected paths, and the worst-case e2e delay is calculated for each flow. Then, the paths are reselected by employing a random transition between the states. In this process, the local optimization is avoided by transiting to a distant state at low probability. The procedure of the proposed MCMC method is described in Algorithm 1.

Algorithm 1: MCMC sequence

SelectInitialPath()
$d_{best} \leftarrow MAX$
$count \leftarrow 0$
while $count < threshold$ **do**
  for all $f \in F$ **do**
    CountCompetitiveFlow()
    $d_{f,p}^{Max} \leftarrow$ CalculateDelay()
  if $max(d_{f,p}^{Max}) < d_{best}$ **then**
    $d_{best} \leftarrow max(d_{f,p}^{Max})$
     $\mathcal{S} \rightarrow$ StoreBestPaths()
   $count \leftarrow count + 1$
   ReselectPath()
$\mathcal{S} \leftarrow$ RestoreBestPaths()

IV. Numerical Results

A. Condition

Performance of the proposed routing scheme was evaluated with computer simulations. The simulation environment was an Ubuntu 14.04 server with an Intel Xeon X5690 at 3.47 GHz with 82,478,624 kB memory.

1) Evaluation Method: We calculated the worst-case e2e delay and the optimal routes with the proposed scheme under given conditions. The computed results represent the theoretically best routes. To confirm the validity of the computed routes, the e2e delay was measured with computer simulations using an ns-3 network simulator [27]. The proposed scheme was compared with the shortest path routing algorithm, which is a widely used optimization algorithm where the forwarding paths are computed to minimize the total link metrics. This comparison is reasonable because it is considered to be one of the primary options for carrier networks to reduce propagation delay. This process was iterated with different DU distributions in two types of topologies to verify the generality of the proposed scheme. We measured the computation time to obtain the optimum solution to evaluate the calculation load of the controller.

2) Topology: Figure 5 shows the network topologies we employed in the simulation. They were COST239 and ARPA2, which are widely used in evaluations of carrier networks [28–30]. It was assumed that path-control protocols such as 802.1Qca are employed to configure the forwarding paths for fronthaul streams. The link distance was set, as all bridges are included in a 10 km square area. For each topology, two CUs were connected to different randomly selected bridges in the fronthaul network. The link distance between a bridge and CU was 0.2 km. A certain number of DUs were randomly connected to one of the bridges, and they communicate with one of the two CUs via the fronthaul network. This is because the distribution of DUs is determined by demand distribution in reality. The link distance of a bridge and DU was randomly determined in the 0.2–1 km range. The number of DUs was set to 50, 60, 70, 80, 90, and 100. We iterated simulations 50 times with different DU distributions for each number of DUs.

3) Traffic: Each DU synchronously sent a 9000 byte burst every 2 ms to simulate TDD, where the synchronization timing error was set as category C (1.38 μs) [10]. The burst size is set based on [31]. The reason why the data rate for DUs is small for LTE-A or 5G is that multiple-input and multiple-output (MIMO) and carrier aggregation (CA) are not considered in the simulation. The threshold for worst-case delay τ was set as 250 μs, which is the maximum allowed one-way latency defined in [32]. The other simulation parameters are shown in Table II.

4) Routing Procedure: For each iteration, the optimal forwarding paths were computed with the proposed routing scheme: (1) The candidate path sets for fronthaul streams were generated based on the randomly determined DU distribution. (2) The path-selection and the e2e delay estimation are repeated with the MCMC method. Then, the computed solution was set to the traffic simulator and the e2e delay was measured.

B. Results

Figure 6 shows the worst-case e2e delay measured in the ns-3 simulation for each case of DU distribution. The results with the proposed routing scheme and the shortest path algorithm for the same case, i.e., the pair of worst-case e2e delay ($d^{\mathrm{Max}}_{\mathrm{prop},i}$, $d^{\mathrm{Max}}_{\mathrm{short},i}$) for i-th case, are compared.

TABLE II
Parameters

Item	Value
Number of CUs	2
Number of DUs	50, 60, 70, 80, 90, 100
Iterations for each number of DUs	50
Simulation time	5 s
Capacity of DU-bridge link	1 Gbps
Capacity of bridge-bridge link	10 Gbps
Capacity of CU-bridge link	100 Gbps
Burst size m	9000 bytes
Processing delay d_n^{prc}	1 μs
Propagation delay d_l^{prop}	5 μs/km
Maximum size of path set k_f	2
Threshold for MCMC	1,000,000
Threshold for worst-case delay τ	250 μs

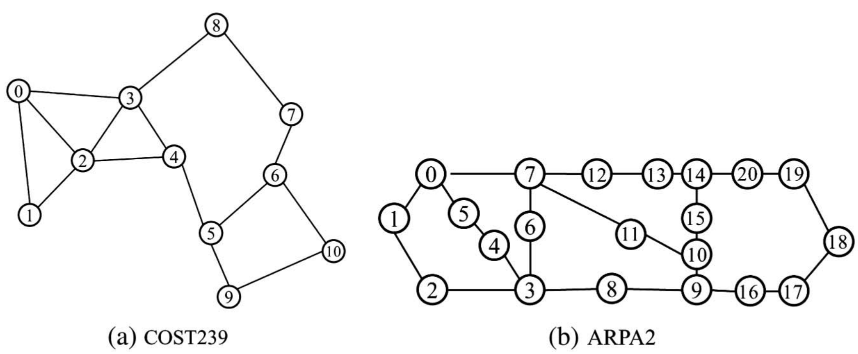

Fig. 5. Simulation topology.

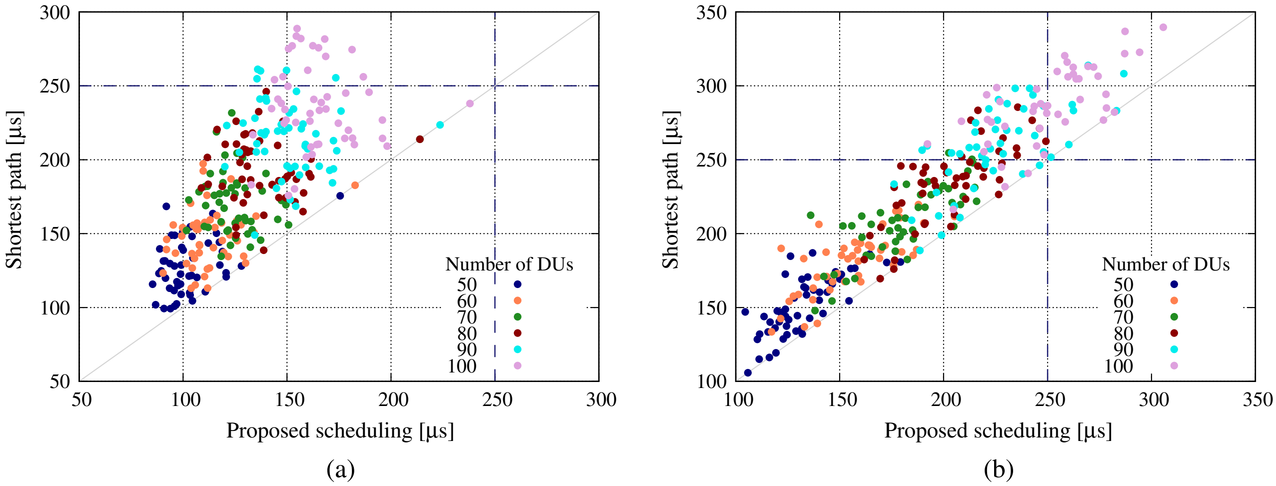

Fig. 6. Worst-case e2e delay for each DU distribution. (a) COST239. (b) ARPA2.

For each topology, 300 pairs of results were acquired with 300 iterations. Figure 7 shows the distribution for improvement value with the proposed scheme.

Figures 6(a) and 7(a) depict the results for COST239. The worst-case e2e delay ranges from about 100–300 µs. The results with the proposed scheme are always equal to or better than those with the shortest path algorithm. The proposed routing scheme reduces the worst-case delay by reducing the queuing delay, even if the propagation delay increases from the shortest path. With the shortest path algorithm, $d_{\text{short}}^{\text{Max}}$ exceeds the threshold τ in 7% of cases, whereas $d_{\text{prop}}^{\text{Max}} < \tau$ is always satisfied. The improvement value is several tens of microseconds, as shown in Fig. 7(a). In about 50% of cases, the proposed scheme reduces the worst-case delay by over 50 µs.

Figures 6(b) and 7(b) depict the results for ARPA2. The trend is the same as the results of COST239. The proposed scheme outperforms the shortest path algorithm. When the shortest paths are employed, the maximum delay of some flows exceeds the threshold in 30% of cases because of the queuing delay. This percentage is improved to 10% with the proposed scheme. If too many DUs are connected to the network, $d_{\text{prop}}^{\text{Max}}$ cannot be less than τ even though the proposed scheme is employed.

Figure 8 shows the number of iterations and computation time required to obtain the solution for COST239 with the proposed scheme. They represent the cumulative distribution function for finding the solution that satisfies the delay threshold. The number of iterations required to find the solution increases with the number of DUs. If the number of DUs is less than 100, the computation can finish within 100,000 iterations and 1 min. When the number of DUs is 100, it requires several minutes. Because the route calculation is executed only if the physical topology of the network such as the distribution of CUs and DUs changes, several minutes of calculation is not a problem. It is reasonable to determine the threshold for stopping the iteration based on the distribution of the

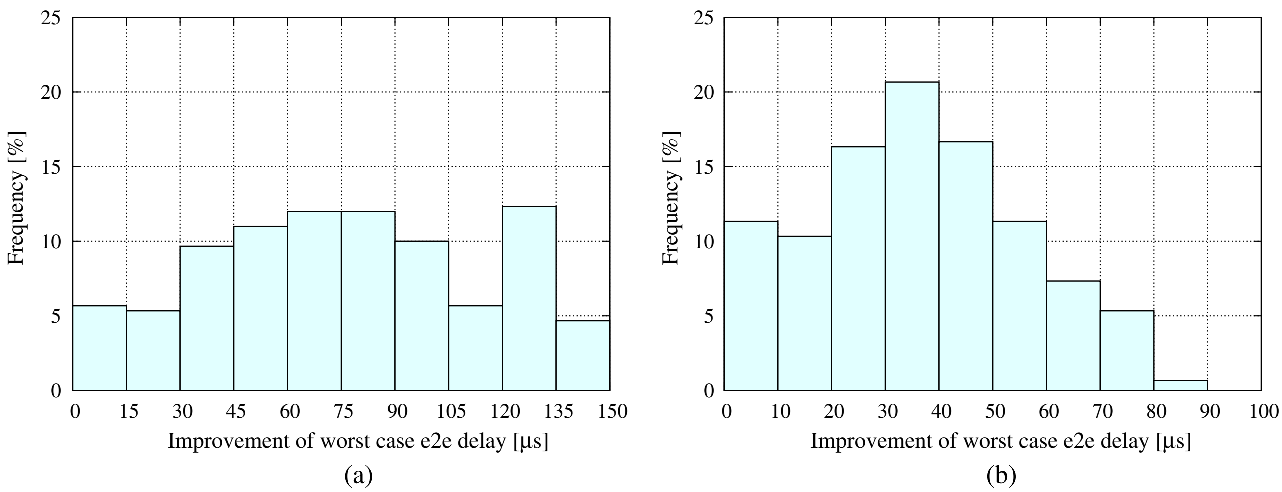

Fig. 7. Improvement of worst-case e2e delay. (a) COST239. (b) ARPA2.

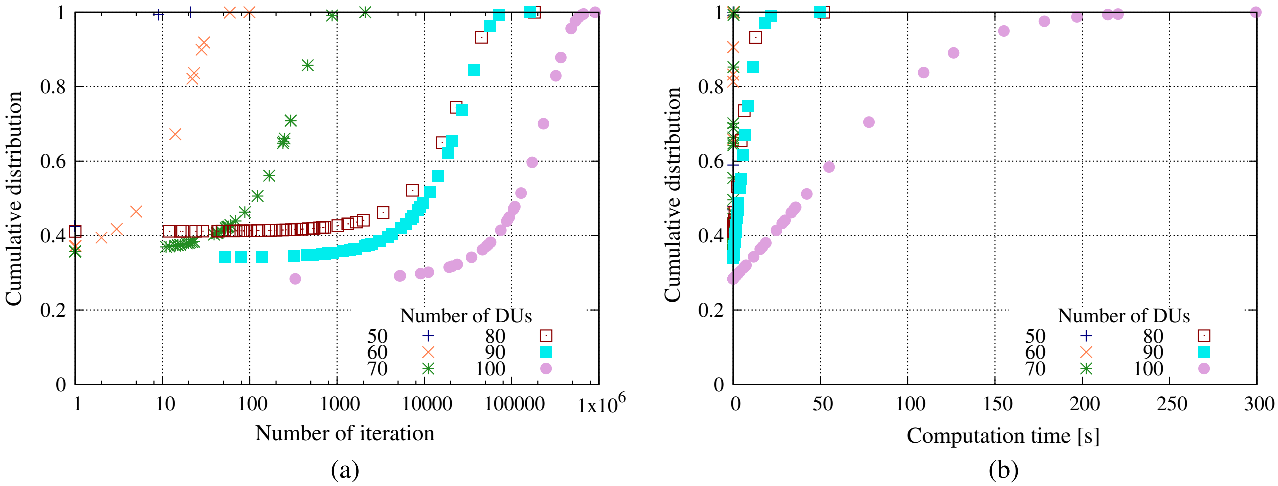

Fig. 8. Required iterations for COST239. (a) Number of iterations. (b) Computation time.

required iterations to find the solution. In this case, 1,000,000 is sufficient. Moreover, it is easy to parallelize the calculation for the proposed routing to reduce the computation time.

From these results, we confirmed that the proposed routing scheme can adequately reduce the queuing delay and minimize the worst-case e2e delay, irrespective of the network topology and DU distribution.

V. Conclusion

In this paper we proposed a novel low-latency routing scheme to satisfy the latency requirements in a fronthaul bridged network with path-control protocols. The proposed routing scheme formulates the worst-case e2e delay of each fronthaul stream based on the distribution of DUs and CUs, the topology of the fronthaul network, and the propagation delay and metric of the links. The maximum queuing delay is minimized by considering the time synchronization between fronthaul flows and the burst size determined by the TDD subframe length. The optimal paths that minimize the maximum value of the worst-case e2e delay are selected from the candidate path sets for fronthaul flows generated with the k-th shortest path algorithm. Then, the proposed routing scheme judges whether or not the delay requirements are satisfied for all streams. The performance of the proposed scheme was confirmed with computer simulations. From the simulation results, it was confirmed that the proposed scheme can adequately reduce the queuing delay and minimize the worst case e2e delay, irrespective of the network topology and DU distribution.

Acknowledgment

A part of this work was conducted under the R&D contract "Wired-and-Wireless Converged Radio Access Network for Massive IoT Traffic" with the Ministry of Internal Affairs and Communications, Japan, for radio resource enhancement.

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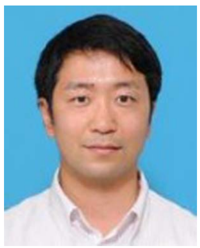

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