Balancing Cost and Completion Time Through Variable Paths With Variable Bandwidth in HPNs

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***Abstract*—In various scientific domains, the continuous generation of vast datasets necessitates their swift transfer over long distances for collaborative data storage and analysis. This is often facilitated by high-performance networks (HPNs) that provide bandwidth reservation services for efficient and reliable data transfer. Typically, the primary objective of data transfer is to achieve the earliest completion time (ECT). However, users may also aim to minimize the financial costs associated with these transfers. Balancing these competing requirements can be complex. This paper examines the trade-off between ECT and cost in data transfers that utilize bandwidth reservation on variable paths with variable bandwidth within dedicated HPNs. We focus on two types of bandwidth reservation requests and their scheduling: (i) minimizing data transfer costs while adhering to a transfer deadline, and (ii) achieving ECT within a specified maximum cost. We demonstrate that both problems are NP-complete and subsequently propose heuristic algorithms to address them. Extensive simulations are conducted to demonstrate their effectiveness and efficiency.**

***Index Terms*—Bandwidth reservation, bandwidth scheduling, resource allocation, big data management, dynamic provisioning, quality of service (QoS)**

I. Introduction

Technological advancements and the extensive use of large-scale applications have resulted in the creation of massive datasets across numerous scientific disciplines. These datasets are typically generated at centralized data centers and require rapid transfer to geographically distributed data centers with substantial processing and storage capacities for data storage and analysis [1], [2]. Ensuring the efficient, reliable, and cost-effective transfer of this vast amount of data is crucial for the timely storage, processing and analysis of particle observations. Dedicated high-performance networks (HPNs) offering bandwidth reservation services have proven to be an effective solution to meet these stringent requirements [3], [4].

Current bandwidth reservation services enable users to specify the characteristics of data transfers and the desired performance metrics within a Bandwidth Reservation Request (BRR). Although achieving the earliest completion time (ECT) of the data transfer is a common primary goal, users might also prioritize cost according to the service provider's model. Scheduling BRRs with a single focus, such as ECT or cost, is relatively straightforward. However, challenges arise when users need reservations that satisfy multiple, concurrent data transfer requirements. For example, a user might require a transfer that is both cost-effective and quick, necessitating a careful balance between ECT and cost. Balancing these factors is inherently complex, as achieving the optimal equilibrium among various needs involves intricate decision-making processes. This complexity is compounded in high-demand scenarios where network resources are limited, and prioritizing one factor over another can lead to suboptimal outcomes for some aspects of the transfer.

This paper tackles the challenge of balancing ECT and cost in data transfers using bandwidth reservation on variable paths with variable bandwidth (VPVB) within HPNs. VPVB entails transferring data through different paths at varying times with a fluctuating transfer rate, adding complexity to the scheduling process. Our study focuses on two specific types of BRRs that navigate this trade-off: (i) BRR-MinC, which aims to minimize transfer cost while meeting a transfer deadline, and (ii) BRR-MinT, which strives for ECT within a specified maximum transfer cost. We demonstrate that both problems are NP-complete, indicating their computational complexity and the difficulty of finding optimal solutions within a reasonable timeframe. We subsequently propose heuristic algorithms designed to provide efficient and practical solutions. These heuristics are tailored to manage the inherent variability in path availability and bandwidth, ensuring that the data transfers can be completed in a cost-effective and timely manner despite the dynamic nature of the network environment. We then conduct extensive simulations to demonstrate the effectiveness and efficiency of the proposed heuristic algorithms.

The structure of this paper is as follows: Section II provides a review of recent literature related to bandwidth reservation. In Section III, we introduce the concepts of bandwidth reservation and present our cost model. Sections IV and V delve into the complexity analysis of the problems, and design of our proposed algorithms. Simulation results are presented in Section VI, and we conclude our work in Section VII.

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II. Related Works

In recent years, many research efforts have been spent on addressing various challenges related to data transfer using bandwidth reservation. Below, we present a concise summary of the notable research findings in this domain in recent years.

Balman *et al.* in [3] introduced a bandwidth scheduling algorithm to determine the bandwidth reservation (BR) with ECT and the shortest duration for a given BRR. Lin and Wu in [1] explored various combinations of paths and bandwidth constraints, formulating four types of advanced bandwidth scheduling problems: fixed/variable paths with fixed/variable bandwidth. They conducted detailed complexity analyses for each problem and proposed corresponding algorithms to achieve the BR with ECT for the received BRR.

Hou *et al.* in [5] addressed bandwidth scheduling with two variable node-disjoint paths, considering fixed or variable bandwidth and negligible or non-negligible path switching delays. These problems were proven NP-complete, and heuristic algorithms were proposed. Zuo *et al.* in [6] examined scheduling maximization for a batch of BRRs, aiming to (i) maximize data transfer and (ii) maximize the number of requests scheduled. Both problems were shown to be NP-complete and difficult to approximate, leading to the development of heuristic algorithms. Hou *et al.* in [7] focused on scheduling multiple user requests with different priorities: advance bandwidth reservation with lower priority and immediate bandwidth reservation with higher priority. The goal was to maximize user satisfaction degree. This problem was also proven NP-complete, with a heuristic algorithm proposed.

Al-Khatib *et al.* [8] studied bandwidth reservation in safety-critical vehicular scenarios, aiming to minimize reservation costs in exact-booking, under-booking, and over-booking situations. Their algorithm optimizes bandwidth allocation dynamically. Zhang *et al.* [9] introduced an elastic bandwidth reservation solution to reduce congestion by combining fixed and dynamic reservation methods. They also proposed a low-cost traffic monitoring framework and a dynamic traffic control algorithm that balances resource utilization and congestion avoidance. Zuo *et al.* [10] investigated intelligent bandwidth scheduling for direct and indirect BRRs. When bandwidth resources are insufficient to meet user-defined intervals, they proposed innovative scheduling algorithms that provide alternative reservations in the nearest intervals, enhancing flexibility and resource efficiency.

III. Bandwidth Reservation Concepts and Data Transfer Cost Model

In this section, we introduce concepts of bandwidth reservation followed by construction of the data transfer cost model.

A. Fundamental Concepts of Bandwidth Reservation

For convenience, we model the dedicated HPN that offers bandwidth reservation services as a weighted graph denoted by $G(V, E)$, where V represents the set of nodes and E represents the set of edges [1]. We define and represent the two types of BRRs, BRR-MinC and BRR-MinT, as follows:

- BRR-MinC $(v_s, v_d, D, [t_S, t_E])$: Minimize the cost of transferring data of size D from source node v_s to destination node v_d by the deadline t_E on VPVB of G.
- BRR-MinT $(v_s, v_d, D, t_S, C_{max})$: Achieving ECT for transferring data of size D from v_s to v_d on VPVB of G, while ensuring the total transfer cost does not exceed the specified maximum cost threshold C_{max}.

In both notations, t_S represents the earliest possible start time for the data transfer.

Each edge $e \in E$ is associated with a series of functions that indicate the residual or available bandwidth over time [1]. These functions, in the form of $B(e, [t_i^e, t_{i+1}^e])$, quantify the available bandwidth of edge e within the time slot $[t_i^e, t_{i+1}^e]$, where $i = 0, 1, \ldots, T_e - 1$. Here T_e denotes the total number of time slots assigned to edge e. In the last time slot $[t_{T_e-1}^e, t_{T_e}^e]$,no bandwidth reservations are made on e, and the available bandwidth of e in this period is referred as as its bandwidth capacity. We define time dots as the starting and ending points of a time slot on an edge.

We construct a sorted set containing unique elements arranged in ascending order. We then add all time dots of G to this sorted set, denoted as $STD = \{t_0, t_1, \ldots, t_n\}$. We define the time interval $[t_i, t_{i+1}]$, $i = 0, 1, \ldots, n-1$, as an intersected time slot. The available bandwidth of edge e within $[t_i, t_{i+1}]$ is represented as $B(e, [t_i, t_{i+1}])$.

We define a time window, denoted as $[t_i, t_j]$, $0 \le i < j \le n$, as a sequence of consecutive intersected time slots $[t_i, t_{i+1}]$, $[t_{i+1}, t_{i+2}]$, ..., $[t_{j-1}, t_j]$. The available bandwidth of edge e within time window $[t_i, t_j]$, denoted by $B(e, [t_i, t_j])$, is the minimum available bandwidth among all the constituent time slots. Mathematically, this can be expressed as $B(e, [t_i, t_j]) = \min(B(e, [t_i, t_{i+1}]), B(e, [t_{i+1}, t_{i+2}]), \ldots, B(e, [t_{j-1}, t_j]))$. Similarly, for a path p represented as $e_0 - e_1 - \cdots - e_{m-1}$, its available bandwidth within time window $[t_i, t_j]$ can be mathematically calculated as $B(p, [t_i, t_j]) = \min(B(e_0, [t_i, t_j]), B(e_1, [t_i, t_j]), \ldots, B(e_{m-1}, [t_i, t_j]))$.

B. Data Transfer Cost Model

We define the bandwidth resource of an edge e within an intersected time slot $[t_i, t_{i+1}]$ as the maximum amount of data e can transfer during that period. This translates to $B(e, [t_i, t_{i+1}]) \cdot (t_{i+1} - t_i)$. At the beginning of this section, we introduced the weighted graph G to represent the dedicated HPN providing bandwidth reservation services. The weight of an edge e, denoted by $w(e)$, signifies the cost coefficient for data transfer on that edge. This coefficient is primarily determined by physical link characteristics such as link materials, distance, and maintenance costs. We assume the cost to transfer data amount d through edge e is $w(e) \cdot d$. The total cost to transfer data amount d along a path p represented as $e_0 - e_1 - \cdots - e_{m-1}$ can be calculated below:

$$\sum_{i=0}^{m-1} w(e_i) \cdot d = d \cdot \sum_{i=0}^{m-1} w(e_i). \tag{1}$$

Here, $\sum_{i=0}^{m-1} w(e_i)$ represents the sum of the weights of all edges in path p, commonly referred to as the path weight and denoted as $w(p)$. Thus, Equation 1 can be simplified to $d \cdot w(p)$.

A BRR is considered successfully scheduled if a bandwidth reservation (BR) can be established on the VPVB from the source node to the destination node, ensuring that the VPVB has sufficient available bandwidth resources to meet all the requirements of the BRR. We represent a BR on VPVB as $\big((p_0, b_0, [t_i, t_{i+1}]), \ldots, (p_{j-1-i}, b_{j-1-i}, [t_{j-1}, t_j]), [t_s, t_e], c\big)$.

- data transfer duration is $[t_s, t_e]$, where $t_s = max(t_S, t_i)$ and $t_e = t_{j-1} + \frac{D - \sum_{k=1}^{j-i-2} b_k \cdot (t_{i+1+k} - t_{i+k}) - b_0 \cdot (t_{i+1} - t_s)}{b_{j-1-i}}$.
- Bandwidth reservation duration is time window $[t_i, t_j]$ even though only a portion of the first and final intersected time slots of $[t_i, t_j]$ is utilized for data transfer [11].
- the total data transfer cost on the reservation paths is c.

From our data transfer cost model, we can derive that the total data transfer cost c can be calculated as:

$$\sum_{k=0}^{j-1-i} w(p_k) \cdot b_k \cdot (t_{i+1+k} - t_{i+k}) \,. \tag{2}$$

Given a BRR-MinC or BRR-MinT, there can often be numerous, possibly infinite, potential BRs. However, we focus on two specific BRs: the one with the minimum data transfer cost, known as BR-MinC, and the one with ECT, known as BR-MinT. For simplicity, we refer to the problems of optimally scheduling the input BRR-MinC and BRR-MinT on the VPVB of G, and identifying their corresponding BR-MinC and BR-MinT, as VPVB-MinC and VPVB-MinT, respectively.

IV. Problem Formulation, NP-complete Proof and Heuristic Algorithm Design of VPVB-MinC

In this section, we formally define VPVB-MinC, provide a proof of its NP-completeness, and present the design and analysis of the heuristic algorithm.

A. Problem Formulation of VPVB-MinC

Given $G(V, E)$ and BRR-MinC $(v_s, v_d, D, [t_S, t_E])$, suppose the sorted set that contains all time dots of G is $STD = \{t_0, t_1, \ldots, t_n\}$ and the set containing all paths from v_s to v_d is $\{p_0, p_1, \ldots, p_{m-1}\}$. The goal of VPVB-MinC is to identify and return the BR-MinC $\big((p_0, b_0, [t_i, t_{i+1}]), \ldots, (p_{j-i-1}, b_{j-i-1}, [t_{j-1}, t_j]), [t_s, t_e], c\big)$ that satisfies the following optimization and constraints:

$$\min \quad \sum_{k=0}^{j-i-1} \sum_{y=0}^{m-1} b_k \cdot (t_{k+i+1} - t_{k+i}) \cdot w(p_y) \cdot x_{(p_y, [t_{k+i}, t_{k+i+1}])} \tag{3a}$$

$$\text{s. t.} \quad max(t_S, t_i) = t_s < t_e = t_{j-1} + \frac{D - \sum_{k=1}^{j-i-2} b_k \cdot (t_{k+i+1} - t_{k+i}) - b_0 \cdot (t_{i+1} - t_s)}{b_{j-i-1}} \le min(t_E, t_j), \tag{3b}$$

$$x_{(p_y, [t_{k+i}, t_{k+i+1}])} \in \{0, 1\}\,,\ \forall y \in \{0, 1, ..., m-1\},\ \forall k \in \{0, 1, ..., j-i-1\}, \tag{3c}$$

$$\sum_{y=0}^{m-1} x_{(p_y, [t_{k+i}, t_{k+i+1}])} = 1,\ \forall k \in \{0, 1, ..., j-i-1\}, \tag{3d}$$

$$b_k \le B\left(p_y, [t_{k+i}, t_{k+i+1}]\right) \ \text{when}\ x_{(p_y, [t_{k+i}, t_{k+i+1}])} = 1,\ \forall y \in \{0, 1, ..., m-1\},\ \forall k \in \{0, 1, ..., j-i-1\}. \tag{3e}$$

B. Complexity Analysis and NP-complete Proof

We prove that VPVB-MinC is NP-complete. First, we establish that VPVB-MinC is in NP. We then demonstrate its NP-hardness by reducing the known NP-hard problem, the Multiple-Choice Knapsack Problem (MCKP), to VPVB-MinC. Due to space constraints, the detailed proof is omitted.

Because of the NP-completeness of VPVB-MinC, we focus on the design of an heuristic algorithm for VPVB-MinC.

C. Algorithm Design and Explanation

Please refer to Algorithm 1 for the detailed algorithm design and pseudocode of Heu-VPVB-MinC. In the worst case, its complexity is $O\left(n \cdot (|E| + |V| \cdot \log |V|)\right)$.

V. Problem Formulation, NP-complete Proof and Heuristic Algorithm Design of VPVB-MinT

In this section, we formally define VPVB-MinT, provide a proof of its NP-completeness, and present the design and analysis of the heuristic algorithm.

A. Problem Formulation of VPVB-MinT

Similar to VPVB-MinC, given $G(V, E)$ and BRR-MinT $(v_s, v_d, D, t_S, C_{max}])$ and with the same supposition of time dots set STD and path set $\{p_0, p_1, \ldots, p_{m-1}\}$, the goal of VPVB-MinT is to identify and return the BR-MinT $\big((p_0, b_0, [t_i, t_{i+1}]), \ldots, (p_{j-i-1}, b_{j-i-1}, [t_{j-1}, t_j]), [t_s, t_e], c\big)$ that satisfies the optimization requirements and constraints listed in 4a to 4f.

$$\min \quad t_e, \text{namely } t_{j-1} + \frac{D - \sum_{k=1}^{j-i-2} b_k \cdot (t_{k+i+1} - t_{k+i}) - b_0 \cdot (t_{i+1} - t_s)}{b_{j-i-1}} \tag{4a}$$

$$\text{s. t.} \quad \sum_{k=0}^{j-i-1} \sum_{y=0}^{m-1} b_k \cdot (t_{k+i+1} - t_{k+i}) \cdot w(p_y) \cdot x_{(p_y,[t_{k+i},t_{k+i+1}])} \leq C_{max}, \tag{4b}$$

$$max(t_S, t_i) = t_s < t_e \leq t_j, \tag{4c}$$

$$x_{(p_y,[t_{k+i},t_{k+i+1}])} \in \{0,1\}, \ \forall y \in \{0,1,...,m-1\}, \ \forall k \in \{0,1,...,j-i-1\}, \tag{4d}$$

$$\sum_{y=0}^{m-1} x_{(p_y,[t_{k+i},t_{k+i+1}])} = 1, \ \forall k \in \{0,1,...,j-i-1\}, \tag{4e}$$

$$b_k \leq B\left(p_y, [t_{k+i}, t_{k+i+1}]\right) \text{ when } x_{(p_y,[t_{k+i},t_{k+i+1}])} = 1, \ \forall y \in \{0,1,...,m-1\}, \ \forall k \in \{0,1,...,j-i-1\}. \tag{4f}$$

Algorithm 1 Heuristic Algorithm for VPVB-MinC (Heu-VPVB-MinC)

INPUT: BRR-MinC $(v_s, v_d, D, [t_S, t_E])$
OUTPUT: Estimated BR-MinC of the input BRR-MinC or $NULL$ if no BR exists.

1: Create a sorted set STD containing all the time dots of G, and then identify index u of the largest element in STD that is no larger than t_S and index v of the smallest element that is no less than t_E;
2: Declare and initialize data transfer size $d = 0$ and path list $maxPaths = \varnothing$;
3: **for** $u \leq i \leq (v-1)$ **do**
4: Run Dijkstra's algorithm to return the path p with the largest amount of available bandwidth (the widest path) from v_s to v_d within intersected time slot $[t_i, t_{i+1}]$;
5: $maxPaths[i-u] = p$;
6: $d += B(p, [t_i, t_{i+1}]) \cdot (min(t_E, t_{i+1}) - max(t_S, t_i))$;
7: **if** $d \geq D$ **then**
8: Declare and initialize data transfer cost $c = 0$ and number list $bList = \varnothing$;
9: **for** $0 \leq j \leq (i-u)$ **do**
10: $bList[j] = \lceil \frac{B(maxPaths[j],[t_{u+j},t_{u+j+1}]) \cdot D}{d \cdot \delta} \rceil \cdot \delta$;
11: $c += w(p) \cdot bList[j] \cdot (t_{u+j+1} - t_{u+j})$;
12: **return** estimated BR-MinC $\big((maxPaths[0], bList[0], [t_u, t_{u+1}]), \ldots, (maxPaths[i-u], bList[i-u], [t_i, t_{i+1}]), [t_S, min(t_E, t_{i+1})], c\big)$;
13: **return** $NULL$.

Algorithm 2 Heuristic Algorithm for VPVB-MinT (Heu-VPVB-MinT)

INPUT: BRR-MinT $(v_s, v_d, D, t_S, C_{max})$
OUTPUT: Estimated BR-MinT of the input BRR-MinT or $NULL$ if no BR exists.

1: Create a sorted set STD containing all the time dots of G and then identify index u of the largest element in STD that is no larger than t_S;
2: Declare and initialize path HashMap $maxPaths = \varnothing$;
3: **for** $u \leq j \leq (|STD|-2)$ **do**
4: Declare and initialize data transfer size $d = 0$, data transfer cost $c = 0$;
5: **for** $j \leq i \leq (|STD|-2)$ **do**
6: **if** $maxPaths.keySet$ does not contain i **then**
7: Run Dijkstra's algorithm to return the path p with the largest amount of available bandwidth (the widest path) from v_s to v_d within intersected time slot $[t_i, t_{i+1}]$;
8: $maxPaths.put(i, p)$;
9: $d += B(maxPaths.get(i), [t_i, t_{i+1}]) \cdot (t_{i+1} - max(t_S, t_i))$;
10: $c += w(p) \cdot B(maxPaths.get(i), [t_i, t_{i+1}]) \cdot (t_{i+1} - t_i)$;
11: **if** $d \geq D$ or $c \geq C_{max}$ **then**
12: **if** not $(c \leq C_{max}$ and $d \geq D)$ **then**
13: Continue the loop in Line 3;
14: **return** estimated BR-MinT $\big((maxPaths.get(j), B(maxPaths.get(j), [t_j, t_{j+1}]), [t_j, t_{j+1}]), \ldots, (maxPaths.get(i), B(maxPaths.get(i), [t_i, t_{i+1}]), [t_i, t_{i+1}]), [t_S, t_{i+1} - \frac{d-D}{B(maxPaths.get(i),[t_i,t_{i+1}])}], c\big)$;
15: **return** $NULL$.

B. Complexity Analysis and NP-complete Proof

We also prove that VPVB-MinT is NP-complete. Similar to VPVB-MinC, we show that VPVB-MinT belongs to NP. We then use the MCKP to demonstrate its NP-hardness. Due to space constraints, we omit the detailed proof. As with VPVB-MinC, we also focus on designing a heuristic algorithm.

C. Algorithm Design and Explanation

Please refer to Algorithm 2 for the detailed algorithm design and pseudocode of Heu-VPVB-MinT. In the worst case, its complexity is $O\left(n^2 + n \cdot (|E| + |V| \cdot \log |V|)\right)$.

VI. Performance Evaluation

The On-Demand Secure Circuits and Advance Reservation System (OSCARS), developed by ESnet, stands as a prominent bandwidth reservation service that has garnered widespread

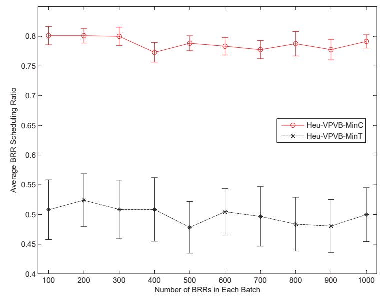

Fig. 1. BRR scheduling ratio by Heu-VPVB-MinC and Heu-VPVB-MinT.

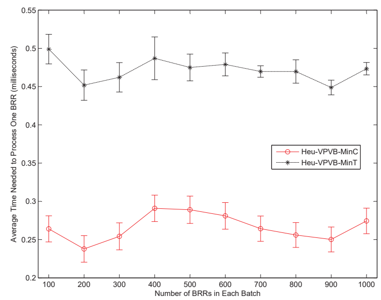

Fig. 2. Average time needed to process one BRR by Heu-VPVB-MinC and Heu-VPVB-MinT.

adoption within the scientific community [4]. To ensure a rigorous and precise evaluation of its performance, we construct a network topology that faithfully emulates the intricate infrastructure of the actual ESnet network.

We conducted ten simulations, each labeled as "simulation i" for $1 \leq i \leq 10$. In each, we generated ten batches of BRRs, with each batch containing $i \times 100$ BRRs. For each BRR, two nodes, v_s and v_d, were randomly selected. The bandwidth unit was set to 100. The data size, D, was a random integer between 10 and 2000 times the bandwidth unit. The start time, t_S, was between 0 and 19, and the end time, t_E, was an integer between t_S and 20. The maximum cost, C_{max}, was set to 0.003 times D. Edge weights were random integers between 1 and 10, divided by 10000. Both algorithms processed identical BRR batches to ensure fair evaluation. Post-processing, we collected performance metrics and generated Figures 1–4. Each figure displays average performance measurements with variances calculated at a 95% confidence level.

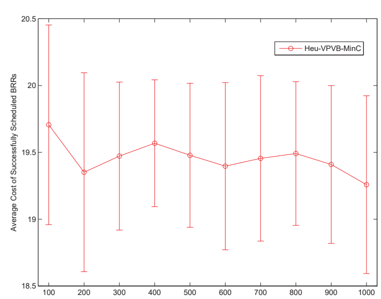

Fig. 3. Average data transfer cost of scheduled BRRs by Heu-VPVB-MinC.

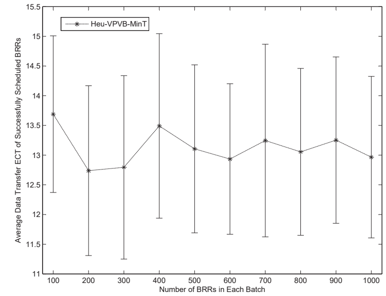

Fig. 4. Average data transfer ECT of scheduled BRRs by Heu-VPVB-MinT.

VII. Conclusion

This paper examines the challenges of bandwidth reservation through variable paths with variable bandwidth (VPVB) in high-performance networks (HPNs). We address two key problems: VPVB-MinC, which minimizes data transfer costs while meeting deadlines, and VPVB-MinT, which seeks the earliest completion time within a specified maximum cost. Our research establishes that both problems are NP-complete, indicating significant computational challenges in finding optimal solutions. To address these, we propose heuristic algorithms that balance efficiency and effectiveness, verified through extensive simulations. Future research will explore similar trade-offs in other data transfer scenarios within HPNs.

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