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# A Computation and Communication Efficient Method for Distributed Nonconvex Problems in the Partial Participation Setting

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## Abstract

1 We present a new method that includes three key components of distributed opti-  
2 mization and federated learning: variance reduction of stochastic gradients, partial  
3 participation, and compressed communication. We prove that the new method has  
4 optimal oracle complexity and state-of-the-art communication complexity in the  
5 partial participation setting. Regardless of the communication compression feature,  
6 our method successfully combines variance reduction and partial participation: we  
7 get the optimal oracle complexity, never need the participation of all nodes, and do  
8 not require the bounded gradients (dissimilarity) assumption.

## 9 1 Introduction

10 Federated and distributed learning have become very popular in recent years (Konečný et al., 2016;  
11 McMahan et al., 2017). The current optimization tasks require much computational resources and  
12 machines. Such requirements emerge in machine learning, where massive datasets and computations  
13 are distributed between cluster nodes (Lin et al., 2017; Ramesh et al., 2021). In federated learning,  
14 nodes, represented by mobile phones, laptops, and desktops, do not send their data to a server due to  
15 privacy and their huge number (Ramaswamy et al., 2019), and the server remotely orchestrates the  
16 nodes and communicates with them to solve an optimization problem.

17 As in classical optimization tasks, one of the main current challenges is to find **computationally**  
18 **efficient** optimization algorithms. However, the nature of distributed problems induces many other  
19 (Kairouz et al., 2021), including i) **partial participation** of nodes in algorithm steps: due to stragglers  
20 (Li et al., 2020) or communication delays (Vogels et al., 2021), ii) **communication bottleneck**: even  
21 if a node participates, it can be costly to transmit information to a server or other nodes (Alistarh  
22 et al., 2017; Ramesh et al., 2021; Kairouz et al., 2021; Sapio et al., 2019; Narayanan et al., 2019). It  
23 is necessary to develop a method that considers these problems.

## 24 2 Optimization Problem

25 Let us consider the nonconvex distributed optimization problem

$$\min_{x \in \mathbb{R}^d} \left\{ f(x) := \frac{1}{n} \sum_{i=1}^n f_i(x) \right\}, \quad (1)$$

26 where  $f_i : \mathbb{R}^d \rightarrow \mathbb{R}$  is a smooth nonconvex function for all  $i \in [n] := \{1, \dots, n\}$ . The full  
27 information about function  $f_i$  is stored on  $i^{\text{th}}$  node. The communication between nodes is maintained  
28 in the parameters server fashion (Kairouz et al., 2021): we have a server that receives compressed

information from nodes, updates a state, and broadcasts an updated model.<sup>1</sup> Since we work in the nonconvex world, our goal is to find an  $\varepsilon$ -solution ( $\varepsilon$ -stationary point) of (1): a (possibly random) point  $\hat{x} \in \mathbb{R}^d$ , such that  $\mathbb{E}[\|\nabla f(\hat{x})\|^2] \leq \varepsilon$ .

We consider three settings:

1. **Gradient Setting.** The  $i^{\text{th}}$  node has only access to the gradient  $\nabla f_i : \mathbb{R}^d \rightarrow \mathbb{R}^d$  of function  $f_i$ . Moreover, the following assumptions for the functions  $f_i$  hold.

**Assumption 1.** *There exists  $f^* \in \mathbb{R}$  such that  $f(x) \geq f^*$  for all  $x \in \mathbb{R}$ .*

**Assumption 2.** *The function  $f$  is  $L$ -smooth, i.e.,  $\|\nabla f(x) - \nabla f(y)\| \leq L\|x - y\|$  for all  $x, y \in \mathbb{R}^d$ .*

**Assumption 3.** *The functions  $f_i$  are  $L_i$ -smooth for all  $i \in [n]$ . Let us define  $\hat{L}^2 := \frac{1}{n} \sum_{i=1}^n L_i^2$ .<sup>2</sup>*

2. **Finite-Sum Setting.** The functions  $\{f_i\}_{i=1}^n$  have the finite-sum form

$$f_i(x) = \frac{1}{m} \sum_{j=1}^m f_{ij}(x), \quad \forall i \in [n], \quad (2)$$

where  $f_{ij} : \mathbb{R}^d \rightarrow \mathbb{R}$  is a smooth nonconvex function for all  $j \in [m]$ . We assume that Assumptions 1, 2 and 3 hold and the following assumption.

**Assumption 4.** *The function  $f_{ij}$  is  $L_{ij}$ -smooth for all  $i \in [n], j \in [m]$ . Let  $L_{\max} := \max_{i \in [n], j \in [m]} L_{ij}$ .*

3. **Stochastic Setting.** The function  $f_i$  is an expectation of a stochastic function,

$$f_i(x) = \mathbb{E}_{\xi} [f_i(x; \xi)], \quad \forall i \in [n], \quad (3)$$

where  $f_i : \mathbb{R}^d \times \Omega_{\xi} \rightarrow \mathbb{R}$ . For a fixed  $x \in \mathbb{R}$ ,  $f_i(x; \xi)$  is a random variable over some distribution  $\mathcal{D}_i$ , and, for a fixed  $\xi \in \Omega_{\xi}$ ,  $f_i(x; \xi)$  is a smooth nonconvex function. The  $i^{\text{th}}$  node has only access to a stochastic gradients  $\nabla f_i(\cdot; \xi_{ij})$  of the function  $f_i$  through the distribution  $\mathcal{D}_i$ , where  $\xi_{ij}$  is a sample from  $\mathcal{D}_i$ . We assume that Assumptions 1, 2 and 3 hold and the following assumptions.

**Assumption 5.** *For all  $i \in [n]$  and for all  $x \in \mathbb{R}^d$ , the stochastic gradient  $\nabla f_i(x; \xi)$  is unbiased and has bounded variance, i.e.,  $\mathbb{E}_{\xi} [\nabla f_i(x; \xi)] = \nabla f_i(x)$ , and  $\mathbb{E}_{\xi} [\|\nabla f_i(x; \xi) - \nabla f_i(x)\|^2] \leq \sigma^2$ , where  $\sigma^2 \geq 0$ .*

**Assumption 6.** *For all  $i \in [n]$  and for all  $x, y \in \mathbb{R}$ , the stochastic gradient  $\nabla f_i(x; \xi)$  satisfies the mean-squared smoothness property, i.e.,  $\mathbb{E}_{\xi} [\|\nabla f_i(x; \xi) - \nabla f_i(y; \xi)\|^2] \leq L_{\sigma}^2 \|x - y\|^2$ .*

We compare algorithms using the *oracle complexity*, i.e., the number of (stochastic) gradients that each node has to calculate to get  $\varepsilon$ -solution, and the *communication complexity*, i.e., the number of bits that each node has to send to the server to get  $\varepsilon$ -solution.

## 2.1 Unbiased Compressors

We use the concept of unbiased compressors to alleviate the communication bottleneck. The unbiased compressors quantize and/or sparsify vectors that the nodes send to the server.

**Definition 1.** A stochastic mapping  $\mathcal{C} : \mathbb{R}^d \rightarrow \mathbb{R}^d$  is an *unbiased compressor* if there exists  $\omega \in \mathbb{R}$  such that

$$\mathbb{E}[\mathcal{C}(x)] = x, \quad \mathbb{E}[\|\mathcal{C}(x) - x\|^2] \leq \omega \|x\|^2, \quad (4)$$

for all  $x \in \mathbb{R}^d$ .

<sup>1</sup>Note that this strategy can be used in peer-to-peer communication, assuming that the server is an abstraction and all its algorithmic steps are performed on each node.

<sup>2</sup>Note that  $L \leq \hat{L}$ ,  $\hat{L} \leq L_{\max}$ , and  $\hat{L} \leq L_{\sigma}$ .

Table 1: Summary of methods that solve the problem (1) in the stochastic setting (3). Abbr.: *VR* (Variance Reduction) = Does a method have the optimal oracle complexity  $\mathcal{O}\left(\frac{\sigma^2}{\varepsilon} + \frac{\sigma}{\varepsilon^{3/2}}\right)$ ? *PP* (Partial Participation) = Does a method support partial participation from Section 2.2? *CC* = Does a method have the communication complexity equals to  $\mathcal{O}\left(\frac{d}{\sqrt{n\varepsilon}}\right)$ ?

Method	VR	PP	CC	Limitations
<b>SPIDER, SARAH, PAGE, STORM</b> (Fang et al., 2018; Nguyen et al., 2017) (Li et al., 2021a; Cutkosky and Orabona, 2019)	✓	✗	✗	—
<b>MARINA</b> (Gorbunov et al., 2021)	✓	✗ <sup>(a)</sup>	✓ <sup>(b)</sup>	Suboptimal convergence rate (see (Tyurin and Richtárik, 2023)).
<b>FedPAGE</b> (Zhao et al., 2021b)	✗	✗ <sup>(a)</sup>	✗	Suboptimal oracle complexity $\mathcal{O}\left(\frac{\sigma^2}{\varepsilon^2}\right)$ .
<b>FRECON</b> (Zhao et al., 2021a)	✗	✓	✓	—
<b>FedAvg</b> (McMahan et al., 2017; Karimireddy et al., 2020b)	✗	✓	✗	Bounded gradients (dissimilarity) assumption of $f_i$ .
<b>SCAFFOLD</b> (Karimireddy et al., 2020b)	✗	✓	✗	Suboptimal convergence rate <sup>(e)</sup> .
<b>MIME<sup>(c)</sup></b> (Karimireddy et al., 2020a)	✗ <sup>(d)</sup>	✓	✗	Calculates full gradient. Bounded gradients (dissimilarity) assumption of $f_i$ . Suboptimal oracle complexity $\mathcal{O}(1/\varepsilon^{3/2})$ in the setting (2).
<b>CE-LSGD (for Partial Participation)<sup>(c)</sup></b> (Patel et al., 2022) (concurrent work)	✓	✓	✗	Bounded gradients (dissimilarity) assumption of $f_i$ . Suboptimal oracle complexity $\mathcal{O}(1/\varepsilon^{3/2})$ in the setting (2).
<b>DASHA</b> (Tyurin and Richtárik, 2023)	✓ ✗	✗ or ✓	✓ ✓	—
<b>DASHA-PP</b> (new)	✓	✓	✓	—

<sup>(a)</sup> **MARINA** and **FedPAGE**, with a small probability, require the participation of all nodes so that they can not support partial participation from Section 2.2. Moreover, these methods provide suboptimal oracle complexities.

<sup>(b)</sup> On average, **MARINA** provides the compressed communication mechanism with complexity  $\mathcal{O}\left(\frac{d}{\sqrt{n\varepsilon}}\right)$ . However, with a small probability, this method sends non-compressed vectors.

<sup>(c)</sup> Note that **MIME** and **CE-LSGD** can not be directly compared with **DASHA-PP** because **MIME** and **CE-LSGD** consider the online version of the problem (1), and require more strict assumptions.

<sup>(d)</sup> Although **MIME** obtains the convergence rate  $\mathcal{O}\left(\frac{1}{\varepsilon^{3/2}}\right)$  of a variance reduced method, it requires the calculation of the full (exact) gradients.

<sup>(e)</sup> It can be seen when  $\sigma^2 = 0$ . Let us consider the  $s$ -nice sampling of the nodes, then **SCAFFOLD** requires  $\mathcal{O}\left(\frac{n^{3/2}}{\varepsilon s^{3/2}}\right)$  communication rounds to get  $\varepsilon$ -solution, while **DASHA-PP** requires  $\mathcal{O}\left(\frac{\sqrt{n}}{\varepsilon s}\right)$  communication rounds (see Theorem 4 with  $\omega = 0$ ,  $b = \frac{p_a}{2-p_a}$ , and  $p_a = \frac{s}{n}$ ).

We denote a set of stochastic mappings that satisfy Definition 1 as  $\mathbb{U}(\omega)$ . In our methods, the nodes make use of unbiased compressors  $\{\mathcal{C}_i\}_{i=1}^n$ . The community developed a large number of unbiased compressors, including *RandK* (see Definition 5) (Beznosikov et al., 2020; Stich et al., 2018), Adaptive sparsification (Wangni et al., 2018) and Natural compression and dithering (Horváth et al., 2019a). We are aware of correlated compressors by Szlendak et al. (2021) and quantizers by Suresh et al. (2022) that help in the homogeneous regimes, but in this work, we are mainly concentrated on generic heterogeneous regimes, though, for simplicity, assume the independence of the compressors.

**Assumption 7.**  $\mathcal{C}_i \in \mathbb{U}(\omega)$  for all  $i \in [n]$ , and the compressors are statistically independent.

Table 2: Summary of methods that solve the problem (1) in the finite-sum setting (2). Abbr.: *VR* (Variance Reduction) = Does a method have the optimal oracle complexity  $\mathcal{O}\left(m + \frac{\sqrt{m}}{\varepsilon}\right)$ ? *PP* and *CC* are defined in Table 1.

Method	VR	PP	CC	Limitations
<b>SPIDER, PAGE</b> (Fang et al., 2018; Li et al., 2021a)	✓	✗	✗	—
<b>MARINA</b> (Gorbunov et al., 2021)	✓	✗ <sup>(a)</sup>	✓ <sup>(b)</sup>	Suboptimal convergence rate (see (Tyurin and Richtárik, 2023)).
<b>ZeroSARAH</b> (Li et al., 2021b)	✓	✓	✗	Only homogeneous regime, i.e., the functions $f_i$ are equal.
<b>FedPAGE</b> (Zhao et al., 2021b)	✗	✗ <sup>(a)</sup>	✗	Suboptimal oracle complexity $\mathcal{O}\left(\frac{m}{\varepsilon}\right)$ .
<b>DASHA</b> (Tyurin and Richtárik, 2023)	✓	✗	✓	—
<b>DASHA-PP</b> (new)	✓	✓	✓	—

<sup>(a)</sup>, <sup>(b)</sup> : see Table 1.

## 2.2 Nodes Partial Participation Assumptions

We now try to formalize the notion of partial participation. Let us assume that we have  $n$  events  $\{i^{\text{th}} \text{ node is participating}\}$  with the following properties.

**Assumption 8.** *The partial participation of nodes has the following distribution: exists constants  $p_a \in (0, 1]$  and  $p_{aa} \in [0, 1]$ , such that*

1.  $\text{Prob}(i^{\text{th}} \text{ node is participating}) = p_a, \quad \forall i \in [n],$
2.  $\text{Prob}(i^{\text{th}} \text{ and } j^{\text{th}} \text{ nodes are participating}) = p_{aa},$   
for all  $i \neq j \in [n].$
3.  $p_{aa} \leq p_a^2,$

and these events from different communication rounds are independent.

We are not fighting for the full generality and believe that more complex sampling strategies can be considered in the analysis. For simplicity, we settle upon Assumption 8. Standard partial participation strategies, including  $s$ -nice sampling, where the server chooses uniformly  $s$  nodes without replacement ( $p_a = s/n$  and  $p_{aa} = s(s-1)/n(n-1)$ ), and independent participation, where each node independently participates with probability  $p_a$  (due to independence, we have  $p_{aa} = p_a^2$ ), satisfy Assumption 8. In the literature,  $s$ -nice sampling is one of the most popular strategies (Zhao et al., 2021a; Richtárik et al., 2021; Reddi et al., 2020; Konečný et al., 2016).

## 3 Motivation and Related Work

The main goal of our paper is to develop a method for the nonconvex distributed optimization that will include three key features: variance reduction of stochastic gradients, compressed communication, and partial participation. We now provide an overview of the literature (see also Table 1 and Table 2).

### 1. Variance reduction of stochastic gradients

It is important to consider finite-sum (2) and stochastic (3) settings because, in machine learning tasks, either the number of local functions  $m$  is huge or the functions  $f_i$  is an expectation of a stochastic function due to the batch normalization (Ioffe and Szegedy, 2015) or random augmentation (Goodfellow et al., 2016), and it is infeasible to calculate the full gradients analytically. Let us recall the results from the nondistributed optimization. In the gradient setting, the optimal oracle complexity

is  $\mathcal{O}(1/\varepsilon)$ , achieved by the vanilla gradient descent (GD) (Carmon et al., 2020; Nesterov, 2018). In the finite-sum setting and stochastic settings, the optimal oracle complexities are  $\mathcal{O}\left(m + \frac{\sqrt{m}}{\varepsilon}\right)$  and  $\mathcal{O}\left(\frac{\sigma^2}{\varepsilon} + \frac{\sigma}{\varepsilon^{3/2}}\right)$  (Fang et al., 2018; Li et al., 2021a; Arjevani et al., 2019), accordingly, achieved by methods SPIDER, SARAH, PAGE, and STORM from (Fang et al., 2018; Nguyen et al., 2017; Li et al., 2021a; Cutkosky and Orabona, 2019).

## 2. Compressed communication

In distributed optimization (Ramesh et al., 2021; Xu et al., 2021), lossy communication compression can be a powerful tool to increase the communication speed between the nodes and the server. Different types of compressors are considered in the literature, including unbiased compressors (Alistarh et al., 2017; Beznosikov et al., 2020; Szlendak et al., 2021), contractive (biased) compressors (Richtárik et al., 2021), 3PC compressors (Richtárik et al., 2022). We will focus on unbiased compressors because methods DASHA and MARINA (Tyurin and Richtárik, 2023; Szlendak et al., 2021; Gorbunov et al., 2021) that employ unbiased compressors provide the current theoretical state-of-the-art (SOTA) communication complexities.

Many methods analyzed optimization methods with the unbiased compressors (Alistarh et al., 2017; Mishchenko et al., 2019; Horváth et al., 2019b; Gorbunov et al., 2021; Tyurin and Richtárik, 2023). In the gradient setting, the methods MARINA and DASHA by Gorbunov et al. (2021) and Tyurin and Richtárik (2023) establish the current SOTA communication complexity, each method needs  $\frac{1+\omega/\sqrt{n}}{\varepsilon}$  communication rounds to get an  $\varepsilon$ -solution. In the finite-sum and stochastic settings, the current SOTA communication complexity is attained by the DASHA method, while maintaining the optimal oracle complexities  $\mathcal{O}\left(m + \frac{\sqrt{m}}{\varepsilon\sqrt{n}}\right)$  and  $\mathcal{O}\left(\frac{\sigma^2}{\varepsilon n} + \frac{\sigma}{\varepsilon^{3/2}n}\right)$  per node.

## 3. Partial participation

From the beginning of federated learning era, the partial participation has been considered to be the essential feature of distributed optimization methods (McMahan et al., 2017; Konečný et al., 2016; Kairouz et al., 2021). However, previously proposed methods have limitations: i) methods MARINA and FedPAGE from (Gorbunov et al., 2021; Zhao et al., 2021b) still require synchronization of all nodes with a small probability. ii) in the stochastic settings, methods FedAvg, SCAFFOLD, and FRECON with the partial participation mechanism (McMahan et al., 2017; Karimireddy et al., 2020b; Zhao et al., 2021a) provide results without variance reduction techniques from (Fang et al., 2018; Li et al., 2021a; Cutkosky and Orabona, 2019) and, therefore, get suboptimal oracle complexities. Note that FRECON and DASHA reduce the variance *only from compressors* (in the partial participation and stochastic setting). iii) in the finite-sum setting, the ZeroSARAH method by Li et al. (2021b) focuses on the homogeneous regime only (the functions  $f_i$  are equal). iv) The MIME method by Karimireddy et al. (2020a) and the CE-LSGD method (for Partial Participation) by the concurrent paper (Patel et al., 2022) consider the online version of the problem (1). Therefore, MIME and CE-LSGD (for Partial Participation) require stricter assumptions, including the bounded inter-client gradient variance assumption. In the finite-sum setting (2), MIME and CE-LSGD obtain a suboptimal oracle complexity  $\mathcal{O}(1/\varepsilon^{3/2})$  while, in the full participation setting, it is possible to get the complexity  $\mathcal{O}(1/\varepsilon)$ .

## 4 Contributions

We propose a new method DASHA-PP for the nonconvex distributed optimization.

- As far as we know, this is the first method that includes three key ingredients of federated learning methods: *variance reduction of stochastic gradients, compressed communication, and partial participation*.
- Moreover, this is the first method that combines *variance reduction of stochastic gradients and partial participation* flawlessly: i) it gets the optimal oracle complexity ii) does not require the participation of all nodes iii) does not require the bounded gradients assumption of the functions  $f_i$ .
- We prove convergence rates and show that this method has *the optimal oracle complexity and the state-of-the-art communication complexity in the partial participation setting*. Moreover, in our work, we observe a nontrivial side-effect from mixing the variance reduction of stochastic gradients and partial participation. It is a general problem not related to our methods or analysis that we discuss in Section 7.

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**Algorithm 1 DASHA-PP**

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- 1: **Input:** starting point  $x^0 \in \mathbb{R}^d$ , stepsize  $\gamma > 0$ , momentum  $a \in (0, 1]$ , momentum  $b \in (0, 1]$ , probability  $p_{\text{page}} \in (0, 1]$  (only in **DASHA-PP-PAGE**), batch size  $B$  (only in **DASHA-PP-PAGE**, **DASHA-PP-FINITE-MVR** and **DASHA-PP-MVR**), probability  $p_a \in (0, 1]$  that a node is *participating*<sup>(a)</sup>, number of iterations  $T \geq 1$
  - 2: Initialize  $g_i^0 \in \mathbb{R}^d$ ,  $h_i^0 \in \mathbb{R}^d$  on the nodes and  $g^0 = \frac{1}{n} \sum_{i=1}^n g_i^0$  on the server
  - 3: Initialize  $h_{ij}^0 \in \mathbb{R}^d$  on the nodes and take  $h_i^0 = \frac{1}{m} \sum_{j=1}^m h_{ij}^0$  (only in **DASHA-PP-FINITE-MVR**)
  - 4: **for**  $t = 0, 1, \dots, T - 1$  **do**
  - 5:    $x^{t+1} = x^t - \gamma g^t$
  - 6:   Broadcast  $x^{t+1}, x^t$  to all *participating*<sup>(a)</sup> nodes
  - 7:   **for**  $i = 1, \dots, n$  in parallel **do**
  - 8:     **if**  $i^{\text{th}}$  node is *participating*<sup>(a)</sup> **then**
  - 9:       Calculate  $k_i^{t+1}$  using Algorithm 2, 3, 4 or 5
  - 10:        $h_i^{t+1} = h_i^t + \frac{1}{p_a} k_i^{t+1}$
  - 11:        $m_i^{t+1} = C_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right)$
  - 12:        $g_i^{t+1} = g_i^t + m_i^{t+1}$
  - 13:       Send  $m_i^{t+1}$  to the server
  - 14:     **else**
  - 15:        $h_{ij}^{t+1} = h_{ij}^t$  (only in **DASHA-PP-FINITE-MVR**)
  - 16:        $h_i^{t+1} = h_i^t, \quad g_i^{t+1} = g_i^t, \quad m_i^{t+1} = 0$
  - 17:     **end if**
  - 18:   **end for**
  - 19:    $g^{t+1} = g^t + \frac{1}{n} \sum_{i=1}^n m_i^{t+1}$
  - 20: **end for**
  - 21: **Output:**  $\hat{x}^T$  chosen uniformly at random from  $\{x^t\}_{k=0}^{T-1}$
- (a): For the formal description see Section 2.2.
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**Algorithm 2** Calculate  $k_i^{t+1}$  for **DASHA-PP** in the gradient setting. See line 9 in Alg. 1

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- 1:  $k_i^{t+1} = \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))$
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**Algorithm 3** Calculate  $k_i^{t+1}$  for **DASHA-PP-PAGE** in the finite-sum setting. See line 9 in Alg. 1

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- 1: Generate a random set  $I_i^t$  of size  $B$  from  $[m]$  *with replacement*
  - 2:  $k_i^{t+1} = \begin{cases} \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)), \\ \text{with probability } p_{\text{page}} \text{ on all } \textit{participating} \text{ nodes,} \\ \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)), \\ \text{with probability } 1 - p_{\text{page}} \text{ on all } \textit{participating} \text{ nodes} \end{cases}$
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**Algorithm 4** Calc.  $k_i^{t+1}$  for **DASHA-PP-FINITE-MVR** in the finite-sum setting. See line 9 in Alg. 1

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- 1: Generate a random set  $I_i^t$  of size  $B$  from  $[m]$  *without replacement*
  - 2:  $k_{ij}^{t+1} = \begin{cases} \frac{m}{B} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))), & j \in I_i^t, \\ 0, & j \notin I_i^t \end{cases}$
  - 3:  $h_{ij}^{t+1} = h_{ij}^t + \frac{1}{p_a} k_{ij}^{t+1}$
  - 4:  $k_i^{t+1} = \frac{1}{m} \sum_{j=1}^m k_{ij}^{t+1}$
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**Algorithm 5** Calculate  $k_i^{t+1}$  for **DASHA-PP-MVR** in the stochastic setting. See line 9 in Alg. 1

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- 1: Generate i.i.d. samples  $\{\xi_{ij}^{t+1}\}_{j=1}^B$  of size  $B$  from  $\mathcal{D}_i$ .
  - 2:  $k_i^{t+1} = \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}) - b \left( h_i^t - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}) \right)$
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## 5 Algorithm Description and Main Challenges To Partial Participation

We now present **DASHA-PP** (see Algorithm 1), a family of methods to solve the optimization problem (1). When we started investigating the problem, we took **DASHA** as a baseline method for two reasons: the family of algorithms **DASHA** provides the current state-of-the-art communication complexities in the *non-partial participation* setting, and, unlike **MARINA**, it does not send non-compressed gradients and does not synchronize all nodes. Let us briefly discuss the main idea of **DASHA**, its problem in the *partial participation* setting, and why the refinement of **DASHA** is not an exercise.

- In fact, **DASHA** supports the partial participation of nodes in the *gradient setting*. Since the nodes only do the following steps (see full algorithm in Algorithm 6):

$$g_i^{t+1} = g_i^t + C_i (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - a(g_i^t - \nabla f_i(x^t)))$$

The partial participation mechanism (independent participation from Section 2.2) can be easily implemented here if we redefine the compressor and use another one instead:

$$C_{i,p} := \begin{cases} \frac{1}{p}C_i, & \text{with probability } p \\ 0, & \text{with probability } 1 - p \end{cases}$$

With probability  $1 - p$ , a node does not update  $g_i$  and does not send anything to the server. The main observation is that we can do this trick since the nodes only need the points  $x^{t+1}$  and  $x^t$  to do the step.

- However, we focus our attention on partial participation in the finite-sum and stochastic settings. Let us consider the nodes' steps in **DASHA-MVR** (see Algorithm 7):

$$\begin{aligned} h_i^{t+1} &= \nabla f_i(x^{t+1}; \xi_i^{t+1}) + (1 - b)(h_i^t - \nabla f_i(x^t; \xi_i^{t+1})) \\ g_i^{t+1} &= g_i^t + C_i (h_i^{t+1} - h_i^t - a(g_i^t - h_i^t)) \end{aligned}$$

i) The theoretical analysis of **DASHA-PP** is more complicated: while in **DASHA**, the randomness from compressors is independent of the randomness from stochastic gradients, in **DASHA-PP**, these two randomnesses are coupled by the randomness from the partial participation. Moreover, the new methods have to reduce the variance from partial participation.

ii) In the gradient setting, comparing the structure of algorithms **DASHA-PP** and **DASHA**, one can see that in **DASHA-PP** we added at least two crucial things: the momentum  $b$ , which helps to reduce the variance of partial participation randomness, and the proper scaling by  $1/p_a$ . Note that in finite-sum and stochastic settings, in **DASHA-PP-FINITE-MVR** and **DASHA-PP-MVR**, accordingly, the momentum  $b$  plays the dual role; it also helps to reduce the variance of stochastic gradients.

iii) In the finite-sum setting, we present two methods: **DASHA-PP-PAGE** and **DASHA-PP-FINITE-MVR**. The former is based on **PAGE** (Li et al., 2021a) and with small probability  $p_{\text{page}}$  calculates the full gradients of the functions  $f_i$ . The latter always calculates mini-batches, but it needs extra memory  $\mathcal{O}(dm)$  per node to store vectors  $h_{ij}^t$ .

At the first reading of the proofs, we suggest the reader follow the proof of Theorem 2 in the gradient setting, which takes a small part of the paper. Although the proof seems to be dense and large, the size of the appendix is justified by the fact that we consider different settings and PL-condition.

## 6 Theorems

We now present the convergence rates theorems of **DASHA-PP** in different settings. We will compare the theorems with the results of the current state-of-the-art methods, **MARINA** and **DASHA**, that work in the full participation setting. Suppose that **MARINA** or **DASHA** converges to  $\varepsilon$ -solution after  $T$  communication rounds. Then, ideally, we would expect the convergence of the new algorithms to  $\varepsilon$ -solution after up to  $T/p_a$  communication rounds due to the partial participation constraints<sup>3</sup>. The detailed analysis of the algorithms under Polyak-Łojasiewicz condition we provide in Section E. Let us define  $\Delta_0 := f(x^0) - f^*$ .

<sup>3</sup>We check this numerically in Section A.

## 6.1 Gradient Setting

**Theorem 2.** Suppose that Assumptions 1, 2, 3, 7 and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_a}{2-p_a}$ ,

$$\gamma \leq \left( L + \left[ \frac{48\omega(2\omega+1)}{np_a^2} + \frac{16}{np_a^2} \left( 1 - \frac{p_{aa}}{p_a} \right) \right]^{1/2} \hat{L} \right)^{-1},$$

and  $g_i^0 = h_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP), then  $\mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] \leq \frac{2\Delta_0}{\gamma T}$ .

Let us recall the convergence rate of MARINA or DASHA, the number of communication rounds to get  $\varepsilon$ -solution equals  $\mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{\sqrt{n}} \hat{L} \right] \right)$ , while the rate of DASHA-PP equals  $\mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega+1}{p_a \sqrt{n}} \hat{L} \right] \right)$ . Up to Lipschitz constants factors, we get the degeneration up to  $1/p_a$  factor due to the partial participation.

## 6.2 Finite-Sum Setting

**Theorem 3.** Suppose that Assumptions 1, 2, 3, 4, 7, and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_{page} p_a}{2-p_a}$ , probability  $p_{page} \in (0, 1]$ ,

$$\gamma \leq \left( L + \left[ \frac{48\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1-p_{page})L_{\max}^2}{B} \right) + \frac{16}{np_a^2 p_{page}} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1-p_{page})L_{\max}^2}{B} \right) \right]^{1/2} \right)^{-1}$$

and  $g_i^0 = h_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-PAGE) then  $\mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] \leq \frac{2\Delta_0}{\gamma T}$ .

We now choose  $p_{page}$  to balance heavy full gradient and light mini-batch calculations. Let us define  $\mathbb{1}_{p_a} := \sqrt{1 - \frac{p_{aa}}{p_a}} \in [0, 1]$ . Note that if  $p_a = 1$  then  $p_{aa} = 1$  and  $\mathbb{1}_{p_a} = 0$ .

**Corollary 1.** Let the assumptions from Theorem 3 hold and  $p_{page} = B/(m+B)$ . Then DASHA-PP-PAGE needs

$$T := \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + \frac{1}{p_a} \sqrt{\frac{m}{n}} \left( \frac{\mathbb{1}_{p_a} \hat{L}}{\sqrt{B}} + \frac{L_{\max}}{B} \right) \right] \right) \quad (6)$$

communication rounds to get an  $\varepsilon$ -solution and the expected number of gradient calculations per node equals  $\mathcal{O}(m + BT)$ .

The convergence rate the rate of the current state-of-the-art method DASHA-PAGE without partial participation equals  $\mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{\sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + \sqrt{\frac{m}{n}} \frac{L_{\max}}{B} \right] \right)$ . Let us closer compare it with (6). As expected, we see that the second term w.r.t.  $\omega$  degenerates up to  $1/p_a$ . Surprisingly, the third term w.r.t.  $\sqrt{m/n}$  can degenerate up to  $\sqrt{B}/p_a$  when  $\hat{L} \approx L_{\max}$ . Hence, in order to keep degeneration up to  $1/p_a$ , one should take the batch size  $B = \mathcal{O}(L_{\max}^2/\hat{L}^2)$ . This interesting effect we analyze separately in Section 7. The fact that the degeneration is up to  $1/p_a$  we check numerically in Section A.

In the following corollary, we consider RandK compressors (see Definition 5) and show that with the particular choice of parameters, up to the Lipschitz constants factors, DASHA-PP-PAGE gets the optimal oracle complexity and SOTA communication complexity. The choice of the compressor is driven by simplicity, and the following analysis can be used for other unbiased compressors.

**Corollary 2.** Suppose that assumptions of Corollary 1 hold,  $B \leq \min \left\{ \frac{1}{p_a} \sqrt{\frac{m}{n}}, \frac{L_{\max}^2}{\mathbb{1}_{p_a}^2 \hat{L}^2} \right\}^4$ , and we use the unbiased compressor RandK with  $K = \Theta(Bd/\sqrt{m})$ . Then the communication complexity of

<sup>4</sup>If  $\mathbb{1}_{p_a} = 0$ , then  $\frac{L_{\max}^2}{\mathbb{1}_{p_a}^2 \hat{L}^2} = +\infty$



Algorithm 1 is

$$\mathcal{O}\left(d + \frac{L_{\max}\Delta_0 d}{p_a \varepsilon \sqrt{n}}\right), \quad (7)$$

and the expected number of gradient calculations per node equals

$$\mathcal{O}\left(m + \frac{L_{\max}\Delta_0 \sqrt{m}}{p_a \varepsilon \sqrt{n}}\right). \quad (8)$$

The convergence rate of **DASHA-PP-FINITE-MVR** is provided in Section D.5. The conclusions are the same for the method.

### 6.3 Stochastic Setting

We define  $h^t := \frac{1}{n} \sum_{i=1}^n h_i^t$ .

**Theorem 4.** Suppose that Assumptions 1, 2, 3, 5, 6, 7 and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b \in \left(0, \frac{p_a}{2-p_a}\right]$ ,

$$\gamma \leq \left( L + \left[ \frac{48\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1-b)^2 L_\sigma^2}{B} \right) + \frac{12}{np_a b} \left( \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 + \frac{(1-b)^2 L_\sigma^2}{B} \right) \right]^{1/2} \right)^{-1},$$

and  $g_i^0 = h_i^0$  for all  $i \in [n]$  in Algorithm 1 (**DASHA-PP-MVR**). Then

$$\begin{aligned} \mathbb{E} \left[ \left\| \nabla f(\hat{x}^T) \right\|^2 \right] &\leq \frac{1}{T} \left[ \frac{2\Delta_0}{\gamma} + \frac{2}{b} \left\| h^0 - \nabla f(x^0) \right\|^2 \right. \\ &\quad \left. + \left( \frac{32b\omega(2\omega+1)}{np_a^2} + \frac{4 \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a} \right) \left( \frac{1}{n} \sum_{i=1}^n \left\| h_i^0 - \nabla f_i(x^0) \right\|^2 \right) \right] \\ &\quad + \left( \frac{48b^2\omega(2\omega+1)}{p_a^2} + \frac{12b}{p_a} \right) \frac{\sigma^2}{nB}. \end{aligned}$$

In the next corollary, we choose momentum  $b$  and initialize vectors  $h_i^0$  to get  $\varepsilon$ -solution. Let us define

$$\mathbb{1}_{p_a} := \sqrt{1 - \frac{p_{aa}}{p_a}} \in [0, 1].$$

**Corollary 3.** Suppose that assumptions from Theorem 4 hold, momentum  $b = \Theta\left(\min\left\{\frac{p_a}{\omega} \sqrt{\frac{n\varepsilon B}{\sigma^2}}, \frac{p_a n \varepsilon B}{\sigma^2}\right\}\right)$ ,  $\frac{\sigma^2}{n\varepsilon B} \geq 1$ , and  $h_i^0 = \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0)$  for all  $i \in [n]$ , and batch size  $B_{\text{init}} = \Theta\left(\frac{\sqrt{p_a B}}{b}\right)$ , then Algorithm 1 (**DASHA-PP-MVR**) needs

$$\begin{aligned} T &:= \mathcal{O}\left(\frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right. \right. \\ &\quad \left. \left. + \frac{\sigma}{p_a \sqrt{\varepsilon n}} \left( \frac{\mathbb{1}_{p_a} \hat{L}}{\sqrt{B}} + \frac{L_\sigma}{B} \right) \right] + \frac{\sigma^2}{\sqrt{p_a n \varepsilon B}} \right) \end{aligned}$$

communication rounds to get an  $\varepsilon$ -solution and the number of stochastic gradient calculations per node equals  $\mathcal{O}(B_{\text{init}} + BT)$ .

The convergence rate of the **DASHA-SYNC-MVR**, the state-of-the-art method without partial participation, equals  $\mathcal{O}\left(\frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{\sqrt{\varepsilon n}} \frac{L_\sigma}{B} \right] + \frac{\sigma^2}{n\varepsilon B} \right)$ . Similar to Section 6.2, we see that in the regimes when  $\hat{L} \approx L_\sigma$  the third term w.r.t.  $1/\varepsilon^{3/2}$  can degenerate up to  $\sqrt{B}/p_a$ . However, if we take  $B = \mathcal{O}(L_\sigma^2/\hat{L}^2)$ , then the degeneration of the third term will be up to  $1/p_a$ . This effect we analyze in Section 7. The fact that the degeneration is up to  $1/p_a$  we check numerically in Section A.

In the following corollary, we consider **RandK** compressors (see Definition 5) and show that with the particular choice of parameters, up to the Lipschitz constants factors, **DASHA-PP-MVR** gets the optimal oracle complexity and SOTA communication complexity of **DASHA-SYNC-MVR** method.

245 **Corollary 4.** Suppose that assumptions of Corollary 3 hold, batch size  $B \leq \min \left\{ \frac{\sigma}{p_a \sqrt{\varepsilon n}}, \frac{L_\sigma^2}{\frac{1}{p_a^2} L^2} \right\}$ ,  
 246 we take RandK compressors with  $K = \Theta \left( \frac{B d \sqrt{\varepsilon n}}{\sigma} \right)$ . Then the communication complexity equals

$$\mathcal{O} \left( \frac{d\sigma}{\sqrt{p_a} \sqrt{n\varepsilon}} + \frac{L_\sigma \Delta_0 d}{p_a \sqrt{n\varepsilon}} \right), \quad (9)$$

247 and the expected number of stochastic gradient calculations per node equals

$$\mathcal{O} \left( \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} + \frac{L_\sigma \Delta_0 \sigma}{p_a \varepsilon^{3/2} n} \right). \quad (10)$$

248 We are aware that the initial batch size  $B_{\text{init}}$  can be suboptimal w.r.t.  $\omega$  in DASHA-PP-MVR in some  
 249 regimes (see also (Tyurin and Richtárik, 2023)). This is a side effect of mixing the variance reduction  
 250 of stochastic gradients and compression. However, Corollary 4 reveals that we can escape these  
 251 regimes by choosing the parameter  $K$  of RandK compressors in a particular way. To get the complete  
 252 picture, we analyze the same phenomenon under PL condition (see Section E) and provide a new  
 253 method DASHA-PP-SYNC-MVR (see Section F).

## 254 7 The Problem of Estimating the Mean in the Partial Participation Setting

255 We now provide the example to explain why the only choice of  $B = \mathcal{O} \left( \min \left\{ \frac{1}{p_a} \sqrt{\frac{m}{n}}, \frac{L_{\max}^2}{\frac{1}{p_a^2} L^2} \right\} \right)$  and  
 256  $B = \mathcal{O} \left( \min \left\{ \frac{\sigma}{p_a \sqrt{\varepsilon n}}, \frac{L_\sigma^2}{\frac{1}{p_a^2} L^2} \right\} \right)$  in DASHA-PP-PAGE and DASHA-PP-MVR, accordingly, guarantees  
 257 the degeneration up to  $1/p_a$ . This is surprising, because in methods with the variance reduction of  
 258 stochastic gradients (Li et al., 2021a; Tyurin and Richtárik, 2023) we can take the size of batch size  
 259  $B = \mathcal{O} \left( \sqrt{\frac{m}{n}} \right)$  and  $B = \mathcal{O} \left( \frac{\sigma}{\sqrt{\varepsilon n}} \right)$  and guarantee the optimality. Note that the smaller the batch size  
 260  $B$ , the more the server and the nodes have to communicate to get  $\varepsilon$ -solution.

261 Let us consider the task of estimating the mean of vectors in the distributed setting. Suppose that we  
 262 have  $n$  nodes, and each of them contains  $m$  vectors  $\{x_{ij}\}_{j=1}^m$ , where  $x_{ij} \in \mathbb{R}^d$  for all  $i \in [n], j \in [m]$ .  
 263 First, let us consider that each node samples a mini-batch  $I^i$  of size  $B$  with replacement and sends it  
 264 to the server. Then the server calculates the mean of the mini-batches from nodes. One can easily  
 265 show that the variance of the estimator is

$$\begin{aligned} & \mathbb{E} \left[ \left\| \frac{1}{nB} \sum_{i=1}^n \sum_{j \in I^i} x_{ij} - \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m x_{ij} \right\|^2 \right] \\ &= \frac{1}{nB} \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \left\| x_{ij} - \frac{1}{m} \sum_{j=1}^m x_{ij} \right\|^2. \end{aligned} \quad (11)$$

266 Next, we consider the same task in the partial participation setting with  $s$ -nice sampling, i.e., we  
 267 sample a random set  $S \subset [n]$  of  $s \in [n]$  nodes without replacement and receive the mini-batches  
 268 only from the sampled nodes. Such sampling of nodes satisfy Assumption 8 with  $p_a = s/n$  and  
 269  $p_a = s(s-1)/n(n-1)$ . In this case, the variance of the estimator (See Lemma 1 with  $r_i = 0$  and  
 270  $s_i = \sum_{j \in I^i} x_{ij}$ ) is

$$\begin{aligned} & \mathbb{E} \left[ \left\| \frac{1}{sB} \sum_{i \in S} \sum_{j \in I^i} x_{ij} - \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m x_{ij} \right\|^2 \right] \\ &= \frac{1}{sB} \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \underbrace{\left\| x_{ij} - \frac{1}{m} \sum_{j=1}^m x_{ij} \right\|^2}_{\mathcal{L}_{\max}^2} \end{aligned} \quad (12)$$

$$+ \underbrace{\frac{n-s}{s(n-1)} \frac{1}{n} \sum_{i=1}^n \left\| \frac{1}{m} \sum_{j=1}^m x_{ij} - \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m x_{ij} \right\|^2}_{\hat{\mathcal{L}}^2}.$$

Let us assume that  $s \leq n/2$ . Note that (11) scales with any  $B \geq 1$ , while (12) only scales when  $B = \mathcal{O}(\mathcal{L}_{\max}^2/\hat{\mathcal{L}}^2)$ . In other words, for large enough  $B$ , the variance in (12) does not significantly improves with the growth of  $B$  due to the term  $\hat{\mathcal{L}}^2$ . In our proof, due to partial participation, the variance from (12) naturally appears, and we get the same effect. As was mentioned in Sections 6.2 and 6.3, it can be seen in our convergence rate bounds.

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## 415 A Numerical Verification of Theoretical Dependencies



Figure 1: Classification task with the *real-sim* dataset.

416 Our main goal is to verify the dependeces from the theory. We compare **DASHA-PP** with **DASHA**.  
 417 Clearly, **DASHA-PP** can not generally perform better than **DASHA**. In different settings, we verify  
 418 that the bigger  $p_a$ , the closer **DASHA-PP** is to **DASHA**, i.e., **DASHA-PP** converges no slower than  $1/p_a$   
 419 times.

In all experiments, we take the *real-sim* dataset with dimension  $d = 20,958$  and the number of samples equals 72,309 from LIBSVM datasets (Chang and Lin, 2011) (under the 3-clause BSD license), and randomly split the dataset between  $n = 100$  nodes equally, ignoring residual samples. In the finite-sum setting, we solve a classification problem with functions

$$f_i(x) := \frac{1}{m} \sum_{j=1}^m \left( 1 - \frac{1}{1 + \exp(y_{ij} a_{ij}^\top x)} \right)^2,$$

420 where  $a_{ij} \in \mathbb{R}^d$  is the feature vector of a sample on the  $i^{\text{th}}$  node,  $y_{ij} \in \{-1, 1\}$  is the corresponding  
 421 label, and  $m$  is the number of samples on the  $i^{\text{th}}$  node for all  $i \in [n]$ . In the stochastic setting, we  
 422 consider functions

$$f_i(x_1, x_2) := \mathbb{E}_{j \sim [m]} \left[ -\log \left( \frac{\exp(a_{ij}^\top x_1 y_{ij})}{\sum_{y \in \{1, 2\}} \exp(a_{ij}^\top x_y y)} \right) + \lambda \sum_{y \in \{1, 2\}} \sum_{k=1}^d \frac{\{x_y\}_k^2}{1 + \{x_y\}_k^2} \right],$$

423 where  $x_1, x_2 \in \mathbb{R}^d$ ,  $\{\cdot\}_k$  is an indexing operation,  $a_{ij} \in \mathbb{R}^d$  is a feature of a sample on the  $i^{\text{th}}$  node,  
 424  $y_{ij} \in \{1, 2\}$  is a corresponding label,  $m$  is the number of samples located on the  $i^{\text{th}}$  node, constant  
 425  $\lambda = 0.001$  for all  $i \in [n]$ .

426 The code was written in Python 3.6.8 using PyTorch 1.9 (Paszke et al., 2019). A distributed  
 427 environment was emulated on a machine with Intel(R) Xeon(R) Gold 6226R CPU @ 2.90GHz and  
 428 64 cores.

429 We use the standard setting in experiments<sup>5</sup> where all parameters except step sizes are taken as  
 430 suggested in theory. Step sizes are finetuned from a set  $\{2^i \mid i \in [-10, 10]\}$ . We emulate the partial  
 431 participation setting using  $s$ -nice sampling with the number of nodes  $n = 100$ . We consider the  
 432  $\text{Rand}K$  compressor and take the batch size  $B = 1$ . We plot the relation between communication  
 433 rounds and values of the norm of gradients at each communication round.

434 In the finite-sum (Figure 1a) and in the stochastic setting (Figure 1b), we see that the bigger probability  
 435  $p_a = s/n$  to 1, the closer **DASHA-PP** to **DASHA**. Moreover, **DASHA-PP** with  $s = 10$  and  $s = 1$   
 436 converges approximately  $\times 10$  ( $= 1/p_a$ ) and  $\times 100$  ( $= 1/p_a$ ) times slower, accordingly. Our theory  
 437 predicts such behavior.

<sup>5</sup>Code: <https://github.com/mysteryresearcher/dasha-partial-participation>

## 438 B Original DASHA and DASHA-MVR Methods

439 To simplify the discussion and explanation from the main part, we present the algorithms from (Tyurin  
440 and Richtárik, 2023)

---

### Algorithm 6 DASHA

---

```

1: Input: starting point  $x^0 \in \mathbb{R}^d$ , stepsize  $\gamma > 0$ , momentum  $a \in (0, 1]$ , number of iterations  $T \geq 1$ 
2: Initialize  $g_i^0 \in \mathbb{R}^d$  on the nodes and  $g^0 = \frac{1}{n} \sum_{i=1}^n g_i^0$  on the server
3: for  $t = 0, 1, \dots, T - 1$  do
4:    $x^{t+1} = x^t - \gamma g^t$ 
5:   Broadcast  $x^{t+1}, x^t$  to all participating(a) nodes
6:   for  $i = 1, \dots, n$  in parallel do
7:      $m_i^{t+1} = \mathcal{C}_i(\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - a(g_i^t - \nabla f_i(x^t)))$ 
8:      $g_i^{t+1} = g_i^t + m_i^{t+1}$ 
9:     Send  $m_i^{t+1}$  to the server
10:  end for
11:   $g^{t+1} = g^t + \frac{1}{n} \sum_{i=1}^n m_i^{t+1}$ 
12: end for
13: Output:  $\hat{x}^T$  chosen uniformly at random from  $\{x^t\}_{k=0}^{T-1}$ 

```

---



---

### Algorithm 7 DASHA-MVR (with batch size $B = 1$ )

---

```

1: Input: starting point  $x^0 \in \mathbb{R}^d$ , stepsize  $\gamma > 0$ , momentums  $a, b \in (0, 1]$ , number of iterations  $T \geq 1$ 
2: Initialize  $g_i^0 \in \mathbb{R}^d$  on the nodes and  $g^0 = \frac{1}{n} \sum_{i=1}^n g_i^0$  on the server
3: for  $t = 0, 1, \dots, T - 1$  do
4:    $x^{t+1} = x^t - \gamma g^t$ 
5:   Broadcast  $x^{t+1}, x^t$  to all participating(a) nodes
6:   for  $i = 1, \dots, n$  in parallel do
7:      $h_i^{t+1} = \nabla f_i(x^{t+1}; \xi_i^{t+1}) + (1 - b)(h_i^t - \nabla f_i(x^t; \xi_i^{t+1})), \quad \xi_i^{t+1} \sim \mathcal{D}_i$ 
8:      $m_i^{t+1} = \mathcal{C}_i(h_i^{t+1} - h_i^t - a(g_i^t - h_i^t))$ 
9:      $g_i^{t+1} = g_i^t + m_i^{t+1}$ 
10:    Send  $m_i^{t+1}$  to the server
11:  end for
12:   $g^{t+1} = g^t + \frac{1}{n} \sum_{i=1}^n m_i^{t+1}$ 
13: end for
14: Output:  $\hat{x}^T$  chosen uniformly at random from  $\{x^t\}_{k=0}^{T-1}$ 

```

---

## 441 C Auxiliary facts

442 We list auxiliary facts that we use in our proofs:

443 1. For all  $x, y \in \mathbb{R}^d$ , we have

$$\|x + y\|^2 \leq 2\|x\|^2 + 2\|y\|^2 \quad (13)$$

444 2. Let us take a *random vector*  $\xi \in \mathbb{R}^d$ , then

$$\mathbb{E} \left[ \|\xi\|^2 \right] = \mathbb{E} \left[ \|\xi - \mathbb{E}[\xi]\|^2 \right] + \|\mathbb{E}[\xi]\|^2. \quad (14)$$

### 445 C.1 Sampling Lemma

446 This section provides a lemma that we regularly use in our proofs, and it is useful for samplings that  
447 satisfy Assumption 8.

448 **Lemma 1.** *Suppose that a set  $S$  is a random subset of a set  $[n]$  such that*

449 1.  $\mathbf{Prob}(i \in S) = p_a, \quad \forall i \in [n],$

450 2.  $\mathbf{Prob}(i \in S, j \in S) = p_{aa}, \quad \forall i \neq j \in [n],$

451 3.  $p_{aa} \leq p_a^2,$

452 where  $p_a \in (0, 1]$  and  $p_{aa} \in [0, 1]$ . Let us take random independent vectors  $s_i \in \mathbb{R}^d$  for all  $i \in [n]$ ,  
453 nonrandom vector  $r_i \in \mathbb{R}^d$  for all  $i \in [n]$ , and random vectors

$$v_i = \begin{cases} r_i + \frac{1}{p_a} s_i, & i \in S, \\ r_i, & i \notin S, \end{cases}$$

454 then

$$\begin{aligned} & \mathbb{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n v_i - \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n v_i \right] \right\|^2 \right] \\ &= \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E} \left[ \|s_i - \mathbb{E}[s_i]\|^2 \right] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\mathbb{E}[s_i]\|^2 + \frac{p_{aa} - p_a^2}{p_a^2} \left\| \frac{1}{n} \sum_{i=1}^n \mathbb{E}[s_i] \right\|^2 \\ &\leq \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E} \left[ \|s_i - \mathbb{E}[s_i]\|^2 \right] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\mathbb{E}[s_i]\|^2. \end{aligned}$$

455 *Proof.* Let us define additional constants  $p_{an}$  and  $p_{nn}$ , such that

456 1.  $\mathbf{Prob}(i \in S, j \notin S) = p_{an}, \quad \forall i \neq j \in [n],$

457 2.  $\mathbf{Prob}(i \notin S, j \notin S) = p_{nn}, \quad \forall i \neq j \in [n].$

458 Note, that

$$p_{an} = p_{aa} - p_a \quad (15)$$

459 and

$$p_{nn} = 1 - p_{aa} - 2p_{an}. \quad (16)$$

460 Using the law of total expectation and

$$\mathbb{E}[v_i] = p_a \left( r_i + \mathbb{E} \left[ \frac{1}{p_a} s_i \right] \right) + (1 - p_a) r_i = r_i + \mathbb{E}[s_i],$$

461 we have

$$\begin{aligned}
& \mathbb{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n v_i - \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n v_i \right] \right\|^2 \right] \\
&= \frac{1}{n^2} \sum_{i=1}^n \mathbb{E} \left[ \|v_i - (r_i + \mathbb{E}[s_i])\|^2 \right] \\
&\quad + \frac{1}{n^2} \sum_{i \neq j}^n \mathbb{E} [\langle v_i - (r_i + \mathbb{E}[s_i]), v_j - (r_j + \mathbb{E}[s_j]) \rangle] \\
&= \frac{p_a}{n^2} \sum_{i=1}^n \mathbb{E} \left[ \left\| r_i + \frac{1}{p_a} s_i - (r_i + \mathbb{E}[s_i]) \right\|^2 \right] \\
&\quad + \frac{1-p_a}{n^2} \sum_{i=1}^n \|r_i - (r_i + \mathbb{E}[s_i])\|^2 \\
&\quad + \frac{p_{aa}}{n^2} \sum_{i \neq j}^n \mathbb{E} \left[ \left\langle r_i + \frac{1}{p_a} s_i - (r_i + \mathbb{E}[s_i]), r_j + \frac{1}{p_a} s_j - (r_j + \mathbb{E}[s_j]) \right\rangle \right] \\
&\quad + \frac{2p_{an}}{n^2} \sum_{i \neq j}^n \mathbb{E} \left[ \left\langle r_i + \frac{1}{p_a} s_i - (r_i + \mathbb{E}[s_i]), r_j - (r_j + \mathbb{E}[s_j]) \right\rangle \right] \\
&\quad + \frac{p_{nn}}{n^2} \sum_{i \neq j}^n \langle r_i - (r_i + \mathbb{E}[s_i]), r_j - (r_j + \mathbb{E}[s_j]) \rangle.
\end{aligned}$$

462 From the independence of random vectors  $s_i$ , we obtain

$$\begin{aligned}
& \mathbb{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n v_i - \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n v_i \right] \right\|^2 \right] \\
&= \frac{p_a}{n^2} \sum_{i=1}^n \mathbb{E} \left[ \left\| \frac{1}{p_a} s_i - \mathbb{E}[s_i] \right\|^2 \right] \\
&\quad + \frac{1-p_a}{n^2} \sum_{i=1}^n \|\mathbb{E}[s_i]\|^2 \\
&\quad + \frac{p_{aa}(1-p_a)^2}{n^2 p_a^2} \sum_{i \neq j}^n \langle \mathbb{E}[s_i], \mathbb{E}[s_j] \rangle \\
&\quad + \frac{2p_{an}(p_a-1)}{n^2 p_a} \sum_{i \neq j}^n \langle \mathbb{E}[s_i], \mathbb{E}[s_j] \rangle \\
&\quad + \frac{p_{nn}}{n^2} \sum_{i \neq j}^n \langle \mathbb{E}[s_i], \mathbb{E}[s_j] \rangle.
\end{aligned}$$

463 Using (15) and (16), we have

$$\begin{aligned}
& \mathbb{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n v_i - \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n v_i \right] \right\|^2 \right] \\
&= \frac{p_a}{n^2} \sum_{i=1}^n \mathbb{E} \left[ \left\| \frac{1}{p_a} s_i - \mathbb{E}[s_i] \right\|^2 \right] \\
&\quad + \frac{1-p_a}{n^2} \sum_{i=1}^n \|\mathbb{E}[s_i]\|^2
\end{aligned}$$

$$\begin{aligned}
& + \frac{p_{aa} - p_a^2}{n^2 p_a^2} \sum_{i \neq j}^n \langle E[s_i], E[s_j] \rangle \\
& \stackrel{(14)}{=} \frac{1}{n^2 p_a} \sum_{i=1}^n E \left[ \|s_i - E[s_i]\|^2 \right] \\
& + \frac{1 - p_a}{n^2 p_a} \sum_{i=1}^n \|E[s_i]\|^2 \\
& + \frac{p_{aa} - p_a^2}{n^2 p_a^2} \sum_{i \neq j}^n \langle E[s_i], E[s_j] \rangle \\
& = \frac{1}{n^2 p_a} \sum_{i=1}^n E \left[ \|s_i - E[s_i]\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|E[s_i]\|^2 \\
& + \frac{p_{aa} - p_a^2}{p_a^2} \left\| \frac{1}{n} \sum_{i=1}^n E[s_i] \right\|.
\end{aligned}$$

464 Finally, using that  $p_{aa} \leq p_a^2$ , we have

$$\begin{aligned}
& E \left[ \left\| \frac{1}{n} \sum_{i=1}^n v_i - E \left[ \frac{1}{n} \sum_{i=1}^n v_i \right] \right\|^2 \right] \\
& \leq \frac{1}{n^2 p_a} \sum_{i=1}^n E \left[ \|s_i - E[s_i]\|^2 \right] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|E[s_i]\|^2.
\end{aligned}$$

465

□

## 466 C.2 Compressors Facts

467 We define the *RandK* compressor that chooses without replacement  $K$  coordinates, scales them by a  
468 constant factor to preserve unbiasedness and zero-out other coordinates.

**Definition 5.** Let us take a random subset  $S$  from  $[d]$ ,  $|S| = K$ ,  $K \in [d]$ . We say that a stochastic mapping  $\mathcal{C} : \mathbb{R}^d \rightarrow \mathbb{R}^d$  is *RandK* if

$$\mathcal{C}(x) = \frac{d}{K} \sum_{j \in S} x_j e_j,$$

469 where  $\{e_i\}_{i=1}^d$  is the standard unit basis.

470 **Theorem 6.** If  $\mathcal{C}$  is *RandK*, then  $\mathcal{C} \in \mathbb{U} \left( \frac{d}{K} - 1 \right)$ .

471 See the proof in (Beznosikov et al., 2020).

## 472 D Proofs of Theorems

473 There are three different sources of randomness in Algorithm 1: the first one from vectors  $\{k_i^{t+1}\}_{i=1}^n$ ,  
474 the second one from compressors  $\{\mathcal{C}_i\}_{i=1}^n$ , and the third one from availability of nodes. We define  
475  $E_k[\cdot]$ ,  $E_C[\cdot]$  and  $E_{p_a}[\cdot]$  to be conditional expectations w.r.t.  $\{k_i^{t+1}\}_{i=1}^n$ ,  $\{\mathcal{C}_i\}_{i=1}^n$ , and availability,  
476 accordingly, conditioned on all previous randomness. Moreover, we define  $E_{t+1}[\cdot]$  to be a conditional  
477 expectation w.r.t. all randomness in iteration  $t+1$  conditioned on all previous randomness. Note,  
478 that  $E_{t+1}[\cdot] = E_k[E_C[E_{p_a}[\cdot]]]$ .

479 In the case of **DASHA-PP-PAGE**, there are two different sources of randomness from  $\{k_i^{t+1}\}_{i=1}^n$ .  
480 We define  $E_{p_{\text{page}}}[\cdot]$  and  $E_B[\cdot]$  to be conditional expectations w.r.t. the probabilistic switching and  
481 mini-batch indices  $I_i^t$ , accordingly, conditioned on all previous randomness. Note, that  $E_{t+1}[\cdot] =$   
482  $E_B[E_C[E_{p_a}[E_{p_{\text{page}}}[\cdot]]]]$  and  $E_{t+1}[\cdot] = E_B[E_{p_{\text{page}}}[E_C[E_{p_a}[\cdot]]]]$ .

### 483 D.1 Standard Lemmas in the Nonconvex Setting

484 We start the proof of theorems by providing standard lemmas from the nonconvex optimization.

485 **Lemma 2.** Suppose that Assumption 2 holds and let  $x^{t+1} = x^t - \gamma g^t$ . Then for any  $g^t \in \mathbb{R}^d$  and  
 486  $\gamma > 0$ , we have

$$f(x^{t+1}) \leq f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \frac{\gamma}{2} \|g^t - \nabla f(x^t)\|^2. \quad (17)$$

487 *Proof.* Using  $L$ -smoothness, we have

$$\begin{aligned} f(x^{t+1}) &\leq f(x^t) + \langle \nabla f(x^t), x^{t+1} - x^t \rangle + \frac{L}{2} \|x^{t+1} - x^t\|^2 \\ &= f(x^t) - \gamma \langle \nabla f(x^t), g^t \rangle + \frac{L}{2} \|x^{t+1} - x^t\|^2. \end{aligned}$$

488 Next, due to  $-\langle x, y \rangle = \frac{1}{2} \|x - y\|^2 - \frac{1}{2} \|x\|^2 - \frac{1}{2} \|y\|^2$ , we obtain

$$f(x^{t+1}) \leq f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \frac{\gamma}{2} \|g^t - \nabla f(x^t)\|^2.$$

489 □

490 **Lemma 3.** Suppose that Assumption 1 holds and

$$\mathbb{E} [f(x^{t+1})] + \gamma \Psi^{t+1} \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] + \gamma \Psi^t + \gamma C, \quad (18)$$

491 where  $\Psi^t$  is a sequence of numbers,  $\Psi^t \geq 0$  for all  $t \in [T]$ , constant  $C \geq 0$ , and constant  $\gamma > 0$ .  
 492 Then

$$\mathbb{E} [\|\nabla f(\hat{x}^T)\|^2] \leq \frac{2\Delta_0}{\gamma T} + \frac{2\Psi^0}{T} + 2C, \quad (19)$$

493 where a point  $\hat{x}^T$  is chosen uniformly from a set of points  $\{x^t\}_{t=0}^{T-1}$ .

494 *Proof.* By unrolling (18) for  $t$  from 0 to  $T - 1$ , we obtain

$$\frac{\gamma}{2} \sum_{t=0}^{T-1} \mathbb{E} [\|\nabla f(x^t)\|^2] + \mathbb{E} [f(x^T)] + \gamma \Psi^T \leq f(x^0) + \gamma \Psi^0 + \gamma TC.$$

495 We subtract  $f^*$ , divide inequality by  $\frac{\gamma T}{2}$ , and take into account that  $f(x) \geq f^*$  for all  $x \in \mathbb{R}$ , and  
 496  $\Psi^t \geq 0$  for all  $t \in [T]$ , to get the following inequality:

$$\frac{1}{T} \sum_{t=0}^{T-1} \mathbb{E} [\|\nabla f(x^t)\|^2] \leq \frac{2\Delta_0}{\gamma T} + \frac{2\Psi^0}{T} + 2C.$$

497 It is left to consider the choice of a point  $\hat{x}^T$  to complete the proof of the lemma. □

**Lemma 4.** If  $0 < \gamma \leq (L + \sqrt{A})^{-1}$ ,  $L > 0$ , and  $A \geq 0$ , then

$$\frac{1}{2\gamma} - \frac{L}{2} - \frac{\gamma A}{2} \geq 0.$$

498 The lemma can be easily checked with the direct calculation.

499 **D.2 Generic Lemmas**

500 **Lemma 5.** Suppose that Assumptions 7 and 8 hold and let us consider sequences  $g_i^{t+1}$ ,  $h_i^{t+1}$ , and  
 501  $k_i^{t+1}$  from Algorithm 1, then

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \\ & \leq \frac{2\omega}{n^2 p_a} \sum_{i=1}^n \|k_i^{t+1}\|^2 + \frac{a^2((2\omega + 1)p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2, \end{aligned} \quad (20)$$

502 and

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \right] \\ & \leq \frac{2\omega}{p_a} \|k_i^{t+1}\|^2 + \left( \frac{a^2(2\omega + 1 - p_a)}{p_a} + (1-a)^2 \right) \|g_i^t - h_i^t\|^2 \quad \forall i \in [n]. \end{aligned} \quad (21)$$

503 *Proof.* First, we estimate  $\mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right]$ :

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \\ & = \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1} - \mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g^{t+1} - h^{t+1}]]\|^2 \right] \right] + \|\mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g^{t+1} - h^{t+1}]]\|^2, \end{aligned}$$

504 where we used (14). Due to Assumption 8, we have

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g_i^{t+1}]] \\ & = p_a \mathbb{E}_{\mathcal{C}} \left[ g_i^t + \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right] + (1-p_a) g_i^t \\ & = g_i^t + p_a \mathbb{E}_{\mathcal{C}} \left[ \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right] \\ & = g_i^t + k_i^{t+1} - a (g_i^t - h_i^t), \end{aligned}$$

505 and

$$\mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [h_i^{t+1}]] = p_a \mathbb{E}_{\mathcal{C}} \left[ h_i^t + \frac{1}{p_a} k_i^{t+1} \right] + (1-p_a) h_i^t = h_i^t + k_i^{t+1}.$$

506 Thus, we can get

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \\ & = \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1} - \mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g^{t+1} - h^{t+1}]]\|^2 \right] \right] + (1-a)^2 \|g^t - h^t\|^2. \end{aligned}$$

507 Due to the independence of compressors, we can use Lemma 1 with  $r_i = g_i^t - h_i^t$  and  $s_i =$

508  $p_a \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - k_i^{t+1}$ , and obtain

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \\ & \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_{\mathcal{C}} \left[ \left\| p_a \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - k_i^{t+1} - \mathbb{E}_{\mathcal{C}} \left[ p_a \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - k_i^{t+1} \right] \right\|^2 \right] \\ & \quad + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \mathbb{E}_{\mathcal{C}} \left[ p_a \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - k_i^{t+1} \right] \right\|^2 \end{aligned}$$



$$\begin{aligned}
& + (1-a)^2 \|g^t - h^t\|^2 \\
& = \frac{p_a}{n^2} \sum_{i=1}^n \mathbb{E}_{\mathcal{C}} \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right\|^2 \right] \\
& \quad + \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2.
\end{aligned}$$

509 From Assumption 7, we have

$$\begin{aligned}
& \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \\
& \leq \frac{\omega p_a}{n^2} \sum_{i=1}^n \left\| \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right\|^2 + \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \\
& = \frac{\omega}{n^2 p_a} \sum_{i=1}^n \|k_i^{t+1} - a (g_i^t - h_i^t)\|^2 + \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \\
& \stackrel{(13)}{\leq} \frac{2\omega}{n^2 p_a} \sum_{i=1}^n \|k_i^{t+1}\|^2 + \frac{a^2 ((2\omega + 1)p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2.
\end{aligned}$$

510 The second inequality can be proved almost in the same way:

$$\begin{aligned}
& \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \right] \\
& = \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g_i^{t+1} - h_i^{t+1} - \mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g_i^{t+1} - h_i^{t+1}]]\|^2 \right] \right] + \|\mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g_i^{t+1} - h_i^{t+1}]]\|^2 \\
& = \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g_i^{t+1} - h_i^{t+1} - g_i^t + a (g_i^t - h_i^t) + h_i^t\|^2 \right] \right] + (1-a)^2 \|g_i^t - h_i^t\|^2 \\
& = p_a \mathbb{E}_{\mathcal{C}} \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \frac{1}{p_a} k_i^{t+1} + a (g_i^t - h_i^t) \right\|^2 \right] \\
& \quad + a^2 (1-p_a) \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g_i^t - h_i^t\|^2 \\
& \stackrel{(14)}{=} p_a \mathbb{E}_{\mathcal{C}} \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right\|^2 \right] \\
& \quad + a^2 \frac{(1-p_a)^2}{p_a} \|g_i^t - h_i^t\|^2 \\
& \quad + a^2 (1-p_a) \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g_i^t - h_i^t\|^2 \\
& \leq \frac{\omega}{p_a} \|k_i^{t+1} - a (g_i^t - h_i^t)\|^2 \\
& \quad + \frac{a^2 (1-p_a)}{p_a} \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g_i^t - h_i^t\|^2 \\
& \stackrel{(13)}{\leq} \frac{2\omega}{p_a} \|k_i^{t+1}\|^2 + \frac{a^2 (2\omega + 1 - p_a)}{p_a} \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g_i^t - h_i^t\|^2.
\end{aligned}$$

511

□

512 **Lemma 6.** Suppose that Assumptions 2, 7, and 8 hold and let us take  $a = \frac{p_a}{2\omega+1}$ , then

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{n p_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& \quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{n p_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] + \frac{4\gamma\omega(2\omega+1)}{n p_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right].
\end{aligned}$$

513 *Proof.* Due to Lemma 2 and the update step from Line 4 in Algorithm 1, we have

$$\begin{aligned}
& \mathbb{E}_{t+1} [f(x^{t+1})] \\
& \leq \mathbb{E}_{t+1} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \frac{\gamma}{2} \|g^t - \nabla f(x^t)\|^2 \right] \\
& = \mathbb{E}_{t+1} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \frac{\gamma}{2} \|g^t - h^t + h^t - \nabla f(x^t)\|^2 \right] \\
& \stackrel{(14)}{\leq} \mathbb{E}_{t+1} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \left( \|g^t - h^t\|^2 + \|h^t - \nabla f(x^t)\|^2 \right) \right].
\end{aligned}$$

514 Let us fix some constants  $\kappa, \eta \in [0, \infty)$  that we will define later. Combining the last inequality,  
515 bounds (20), (21) and using the law of total expectation, we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] \\
& + \kappa \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& = \mathbb{E} [\mathbb{E}_{t+1} [f(x^{t+1})]] \\
& + \kappa \mathbb{E} [\mathbb{E}_C [\mathbb{E}_{p_a} [\|g^{t+1} - h^{t+1}\|^2]]] + \eta \mathbb{E} \left[ \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \right] \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \left( \|g^t - h^t\|^2 + \|h^t - \nabla f(x^t)\|^2 \right) \right] \\
& + \kappa \mathbb{E} \left[ \frac{2\omega}{n^2 p_a} \sum_{i=1}^n \|k_i^{t+1}\|^2 + \frac{a^2((2\omega+1)p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \right] \\
& + \eta \mathbb{E} \left[ \frac{2\omega}{n p_a} \sum_{i=1}^n \|k_i^{t+1}\|^2 + \left( \frac{a^2(2\omega+1-p_a)}{p_a} + (1-a)^2 \right) \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& = \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( \gamma + \kappa(1-a)^2 \right) \mathbb{E} [\|g^t - h^t\|^2] \\
& + \left( \frac{\kappa a^2((2\omega+1)p_a - p_{aa})}{n p_a^2} + \eta \left( \frac{a^2(2\omega+1-p_a)}{p_a} + (1-a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( \frac{2\kappa\omega}{n p_a} + \frac{2\eta\omega}{p_a} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right].
\end{aligned}$$

516 Now, by taking  $\kappa = \frac{\gamma}{a}$ , we can see that  $\gamma + \kappa(1-a)^2 \leq \kappa$ , and thus

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] \\
& + \frac{\gamma}{a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma}{a} \mathbb{E} [\|g^t - h^t\|^2] \\
& + \left( \frac{\gamma a((2\omega+1)p_a - p_{aa})}{n p_a^2} + \eta \left( \frac{a^2(2\omega+1-p_a)}{p_a} + (1-a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( \frac{2\gamma\omega}{a n p_a} + \frac{2\eta\omega}{p_a} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right].
\end{aligned}$$

517 Next, by taking  $\eta = \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2}$  and considering the choice of  $a$ , one can show that  
 518  $\left( \frac{\gamma a((2\omega+1)p_a - p_{aa})}{np_a^2} + \eta \left( \frac{a^2(2\omega+1-p_a)}{p_a} + (1-a)^2 \right) \right) \leq \eta$ . Thus

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] \\ & + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & + \left( \frac{2\gamma(2\omega+1)\omega}{np_a^2} + \frac{2\gamma((2\omega+1)p_a - p_{aa})\omega}{np_a^3} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right]. \end{aligned}$$

519 Considering that  $p_{aa} \geq 0$ , we can simplify the last term and get

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] \\ & + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & + \frac{4\gamma(2\omega+1)\omega}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right]. \end{aligned}$$

520

□

### 521 D.3 Proof for DASHA-PP

522 **Lemma 7.** Suppose that Assumptions 3 and 8 hold. For  $h_i^{t+1}$  and  $k_i^{t+1}$  from Algorithm 1 (DASHA-PP)  
 523 we have

1.

$$\begin{aligned} & \mathbb{E}_{p_a} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] \\ & \leq \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \|x^{t+1} - x^t\|^2 + \frac{2b^2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2. \end{aligned}$$

2.

$$\begin{aligned} & \mathbb{E}_{p_a} [\|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2] \\ & \leq \frac{2(1-p_a)}{p_a} L_i^2 \|x^{t+1} - x^t\|^2 + \left( \frac{2b^2(1-p_a)}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n]. \end{aligned}$$

3.

$$\|k_i^{t+1}\|^2 \leq 2L_i^2 \|x^{t+1} - x^t\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n].$$

524 *Proof.* First, let us proof the bound for  $\mathbb{E}_k [\mathbb{E}_{p_a} [\|h^{t+1} - \nabla f(x^{t+1})\|^2]]$ :

$$\mathbb{E}_{p_a} [\|h^{t+1} - \nabla f(x^{t+1})\|^2]$$

$$= \mathbb{E}_{p_a} \left[ \left\| h^{t+1} - \mathbb{E}_{p_a} [h^{t+1}] \right\|^2 \right] + \left\| \mathbb{E}_{p_a} [h^{t+1}] - \nabla f(x^{t+1}) \right\|^2.$$

525 Using

$$\mathbb{E}_{p_a} [h_i^{t+1}] = h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))$$

526 and (14), we have

$$\begin{aligned} & \mathbb{E}_{p_a} \left[ \left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] \\ &= \mathbb{E}_{p_a} \left[ \left\| h^{t+1} - \mathbb{E}_{p_a} [h^{t+1}] \right\|^2 \right] + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2. \end{aligned}$$

527 We can use Lemma 1 with  $r_i = h_i^t$  and  $s_i = k_i^{t+1}$  to obtain

$$\begin{aligned} & \mathbb{E}_{p_a} \left[ \left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] \\ & \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \left\| k_i^{t+1} - k_i^{t+1} \right\|^2 + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| k_i^{t+1} \right\|^2 + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2 \\ &= \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2 \\ & \stackrel{(13)}{\leq} \frac{2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 + \frac{2b^2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \left\| h_i^t - \nabla f_i(x^t) \right\|^2 + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2 \\ & \leq \frac{2(p_a - p_{aa}) \hat{L}^2}{n p_a^2} \left\| x^{t+1} - x^t \right\|^2 + \frac{2b^2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \left\| h_i^t - \nabla f_i(x^t) \right\|^2 + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2. \end{aligned}$$

528 In the last in inequality, we used Assumption 3. Now, we prove the second inequality:

$$\begin{aligned} & \mathbb{E}_{p_a} \left[ \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \\ &= \mathbb{E}_{p_a} \left[ \left\| h_i^{t+1} - \mathbb{E}_{p_a} [h_i^{t+1}] \right\|^2 \right] + \left\| \mathbb{E}_{p_a} [h_i^{t+1}] - \nabla f_i(x^{t+1}) \right\|^2 \\ &= \mathbb{E}_{p_a} \left[ \left\| h_i^{t+1} - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\ &= \frac{(1-p_a)^2}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\ & \quad + (1-p_a) \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\ &= \frac{(1-p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\ & \leq \frac{2(1-p_a)}{p_a} L_i^2 \left\| x^{t+1} - x^t \right\|^2 + \left( \frac{2b^2(1-p_a)}{p_a} + (1-b)^2 \right) \left\| h_i^t - \nabla f_i(x^t) \right\|^2. \end{aligned}$$

529 Finally, the third inequality of the theorem follows from (13) and Assumption 3.  $\square$

530 **Theorem 2.** Suppose that Assumptions 1, 2, 3, 7 and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_a}{2-p_a}$ ,

$$\gamma \leq \left( L + \left[ \frac{48\omega(2\omega+1)}{n p_a^2} + \frac{16}{n p_a^2} \left( 1 - \frac{p_{aa}}{p_a} \right) \right]^{1/2} \hat{L} \right)^{-1},$$

531 and  $g_i^0 = h_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP), then  $\mathbb{E} \left[ \left\| \nabla f(\hat{x}^T) \right\|^2 \right] \leq \frac{2\Delta_0}{\gamma T}$ .

532 *Proof.* Let us fix constants  $\nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 6, Lemma 7,  
533 and the law of total expectation, we obtain

$$\mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \left\| g^{t+1} - h^{t+1} \right\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{n p_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \left\| g_i^{t+1} - h_i^{t+1} \right\|^2 \right]$$

$$\begin{aligned}
& + \nu \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& = \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \quad + \nu \mathbb{E} \left[ \mathbb{E}_{p_a} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] \right] + \rho \mathbb{E} \left[ \mathbb{E}_{p_a} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& \quad + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& \quad + \frac{4\gamma\omega(2\omega + 1)}{np_a^2} \mathbb{E} \left[ 2\hat{L}^2 \|x^{t+1} - x^t\|^2 + 2b^2 \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& \quad + \nu \mathbb{E} \left[ \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \|x^{t+1} - x^t\|^2 + \frac{2b^2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \right] \\
& \quad + \rho \mathbb{E} \left[ \frac{2(1-p_a)\hat{L}^2}{p_a} \|x^{t+1} - x^t\|^2 + \left( \frac{2b^2(1-p_a)}{p_a} + (1-b)^2 \right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

534 After rearranging the terms, we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& \quad + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& \quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma\omega(2\omega + 1)\hat{L}^2}{np_a^2} - \nu \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} - \rho \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& \quad + (\gamma + \nu(1-b)^2) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& \quad + \left( \frac{8b^2\gamma\omega(2\omega + 1)}{np_a^2} + \nu \frac{2b^2(p_a - p_{aa})}{np_a^2} + \rho \left( \frac{2b^2(1-p_a)}{p_a} + (1-b)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

535 By taking  $\nu = \frac{\gamma}{b}$ , one can show that  $(\gamma + \nu(1-b)^2) \leq \nu$ , and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \quad + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& \quad + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma\omega(2\omega+1)\widehat{L}^2}{np_a^2} - \frac{2\gamma(p_a - p_{aa})\widehat{L}^2}{bnp_a^2} - \rho \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b(p_a - p_{aa})}{np_a^2} + \rho \left( \frac{2b^2(1-p_a)}{p_a} + (1-b)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

536 Note that  $b = \frac{p_a}{2-p_a}$ , thus

$$\begin{aligned}
& \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b(p_a - p_{aa})}{np_a^2} + \rho \left( \frac{2b^2(1-p_a)}{p_a} + (1-b)^2 \right) \right) \\
& \leq \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b(p_a - p_{aa})}{np_a^2} + \rho(1-b) \right).
\end{aligned}$$

537 And if we take  $\rho = \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}$ , then

$$\left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b(p_a - p_{aa})}{np_a^2} + \rho(1-b) \right) \leq \rho,$$

538 and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma\omega(2\omega+1)\widehat{L}^2}{np_a^2} - \frac{2\gamma(p_a - p_{aa})\widehat{L}^2}{bnp_a^2} \right. \\
& \quad \left. - \frac{16b\gamma\omega(2\omega+1)(1-p_a)\widehat{L}^2}{np_a^3} - \frac{4\gamma(p_a - p_{aa})(1-p_a)\widehat{L}^2}{np_a^3} \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

539 Let us simplify the last inequality. First, note that

$$\frac{16b\gamma\omega(2\omega+1)(1-p_a)\widehat{L}^2}{np_a^3} \leq \frac{16\gamma\omega(2\omega+1)\widehat{L}^2}{np_a^2},$$

540 due to  $b \leq p_a$ . Second,

$$\frac{2\gamma(p_a - p_{aa})\widehat{L}^2}{bnp_a^2} \leq \frac{4\gamma(p_a - p_{aa})\widehat{L}^2}{np_a^3},$$

541 due to  $b \geq \frac{p_a}{2}$ . All in all, we have

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{24\gamma\omega(2\omega+1)\hat{L}^2}{np_a^2} - \frac{8\gamma(p_a - p_{aa})\hat{L}^2}{np_a^3}\right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
&\quad + \frac{\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
\end{aligned}$$

542 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
&\mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
&\quad + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad + \frac{\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
\end{aligned}$$

543 It is left to apply Lemma 3 with

$$\begin{aligned}
\Psi^t &= \frac{(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad + \frac{1}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(\frac{8b\omega(2\omega+1)}{np_a^2} + \frac{2(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right]
\end{aligned}$$

544 to conclude the proof.  $\square$

#### 545 **D.4 Proof for DASHA-PP-PAGE**

546 Let us denote

$$\begin{aligned}
k_{i,1}^{t+1} &:= \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)), \\
k_{i,2}^{t+1} &:= \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)), \\
h_{i,1}^{t+1} &:= \begin{cases} h_i^t + \frac{1}{p_a} k_{i,1}^{t+1}, & i^{\text{th}} \text{ node is participating,} \\ h_i^t, & \text{otherwise,} \end{cases} \\
h_{i,2}^{t+1} &:= \begin{cases} h_i^t + \frac{1}{p_a} k_{i,2}^{t+1}, & i^{\text{th}} \text{ node is participating,} \\ h_i^t, & \text{otherwise,} \end{cases}
\end{aligned}$$

547  $h_1^{t+1} := \frac{1}{n} \sum_{i=1}^n h_{i,1}^{t+1}$ , and  $h_2^{t+1} := \frac{1}{n} \sum_{i=1}^n h_{i,2}^{t+1}$ . Note, that

$$h^{t+1} = \begin{cases} h_1^{t+1}, & \text{with probability } p_{\text{page}}, \\ h_2^{t+1}, & \text{with probability } 1 - p_{\text{page}}. \end{cases}$$



548 **Lemma 8.** Suppose that Assumptions 3, 4, and 8 hold. For  $h_i^{t+1}$  and  $k_i^{t+1}$  from Algorithm 1  
 549 (DASHA-PP-PAGE) we have

1.

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\ & \leq \left( \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} + \frac{(1 - p_{\text{page}})L_{\max}^2}{np_a B} \right) \|x^{t+1} - x^t\|^2 \\ & \quad + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{page}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \|h^t - \nabla f(x^t)\|^2. \end{aligned}$$

2.

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\ & \leq \left( \frac{2(1 - p_a)L_i^2}{p_a} + \frac{(1 - p_{\text{page}})L_{\max}^2}{p_a B} \right) \|x^{t+1} - x^t\|^2 \\ & \quad + \left( \frac{2(1 - p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n]. \end{aligned}$$

3.

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|k_i^{t+1}\|^2 \right] \right] \\ & \leq \left( 2L_i^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \|x^{t+1} - x^t\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n]. \end{aligned}$$

550 *Proof.* First, we prove the first inequality of the theorem:

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\ & = p_{\text{page}} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_1^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] + (1 - p_{\text{page}}) \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_2^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right]. \end{aligned}$$

551 Using

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] = \\ & = p_a h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) + (1 - p_a) h_i^t \\ & = h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)). \end{aligned}$$

552 and

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,2}^{t+1} \right] \right] = \\ & = p_a h_i^t + \mathbb{E}_B \left[ \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) \right] + (1 - p_a) h_i^t \\ & = h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t), \end{aligned}$$

553 we obtain

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\ & \stackrel{(14)}{=} p_{\text{page}} \mathbb{E}_{p_a} \left[ \|h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}]\|^2 \right] + (1 - p_{\text{page}}) \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_2^{t+1} - \mathbb{E}_{p_a} [h_2^{t+1}]\|^2 \right] \right] \end{aligned}$$

$$\begin{aligned}
& + p_{\text{page}} \left\| \mathbb{E}_{p_a} [h_1^{t+1}] - \nabla f(x^{t+1}) \right\|^2 + (1 - p_{\text{page}}) \left\| \mathbb{E}_B [\mathbb{E}_{p_a} [h_2^{t+1}]] - \nabla f(x^{t+1}) \right\|^2 \\
& = p_{\text{page}} \mathbb{E}_{p_a} \left[ \left\| h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}] \right\|^2 \right] + (1 - p_{\text{page}}) \mathbb{E}_B \left[ \left\| h_2^{t+1} - \mathbb{E}_{p_a} [h_2^{t+1}] \right\|^2 \right] \\
& + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \left\| h^t - \nabla f(x^t) \right\|^2. \tag{22}
\end{aligned}$$

554 Next, we consider  $\mathbb{E}_{p_a} \left[ \left\| h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}] \right\|^2 \right]$ . We can use Lemma 1 with  $r_i = h_i^t$  and  $s_i = k_{i,1}^{t+1}$   
555 to obtain

$$\begin{aligned}
& \mathbb{E}_{p_a} \left[ \left\| h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}] \right\|^2 \right] \\
& \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \left\| k_{i,1}^{t+1} - k_{i,1}^{t+1} \right\|^2 + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| k_{i,1}^{t+1} \right\|^2 \\
& = \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\
& \stackrel{(13)}{\leq} \frac{2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{page}}^2} \sum_{i=1}^n \left\| h_i^t - \nabla f_i(x^t) \right\|^2.
\end{aligned}$$

556 From Assumption 3, we have

$$\begin{aligned}
& \mathbb{E}_{p_a} \left[ \left\| h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}] \right\|^2 \right] \\
& \leq \frac{2(p_a - p_{aa})\hat{L}^2}{n p_a^2} \left\| x^{t+1} - x^t \right\|^2 + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{page}}^2} \sum_{i=1}^n \left\| h_i^t - \nabla f_i(x^t) \right\|^2. \tag{23}
\end{aligned}$$

557 Now, we prove the bound for  $\mathbb{E}_B \left[ \left\| h_2^{t+1} - \mathbb{E}_{p_a} [h_2^{t+1}] \right\|^2 \right]$ . Considering that mini-  
558 batches in the algorithm are independent, we can use Lemma 1 with  $r_i = h_i^t$  and  $s_i = k_{i,2}^{t+1}$   
559 to obtain

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_2^{t+1} - \mathbb{E}_{p_a} [h_2^{t+1}] \right\|^2 \right] \right] \\
& \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_B \left[ \left\| k_{i,2}^{t+1} - \mathbb{E}_{p_a} [k_{i,2}^{t+1}] \right\|^2 \right] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \mathbb{E}_B [k_{i,2}^{t+1}] \right\|^2 \\
& = \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_B \left[ \left\| \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\
& = \frac{1}{n^2 p_a B^2} \sum_{i=1}^n \mathbb{E}_B \left[ \sum_{j \in I_i^t} \left\| (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\
& = \frac{1}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \left\| (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\
& \leq \frac{1}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \left\| \nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) \right\|^2 + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2.
\end{aligned}$$

560 Next, we use Assumptions 3 and 4 to get

$$\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_2^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_2^{t+1} \right] \right] \right\|^2 \right] \right] \leq \left( \frac{L_{\max}^2}{np_a B} + \frac{(p_a - p_{aa}) \hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2. \quad (24)$$

561 Applying (23) and (24) into (22), we get

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] \right] \right] \\ & \leq p_{\text{page}} \left( \frac{2(p_a - p_{aa}) \hat{L}^2}{np_a^2} \|x^{t+1} - x^t\|^2 + \frac{2(p_a - p_{aa}) b^2}{n^2 p_a^2 p_{\text{page}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right) + \\ & \quad + (1 - p_{\text{page}}) \left( \frac{L_{\max}^2}{np_a B} + \frac{(p_a - p_{aa}) \hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \\ & \quad + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \|h^t - \nabla f(x^t)\|^2 \\ & \leq \left( \frac{2(p_a - p_{aa}) \hat{L}^2}{np_a^2} + \frac{(1 - p_{\text{page}}) L_{\max}^2}{np_a B} \right) \|x^{t+1} - x^t\|^2 \\ & \quad + \frac{2(p_a - p_{aa}) b^2}{n^2 p_a^2 p_{\text{page}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \|h^t - \nabla f(x^t)\|^2. \end{aligned}$$

562 The proof of the second inequality almost repeats the previous one:

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] \right] \\ & = p_{\text{page}} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] + (1 - p_{\text{page}}) \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,2}^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] \\ & \stackrel{(14)}{=} p_{\text{page}} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] \right\|^2 \right] \right] + (1 - p_{\text{page}}) \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,2}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,2}^{t+1} \right] \right] \right\|^2 \right] \right] \\ & \quad + p_{\text{page}} \left\| \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] - \nabla f_i(x^{t+1}) \right\|^2 + (1 - p_{\text{page}}) \left\| \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,2}^{t+1} \right] \right] - \nabla f_i(x^{t+1}) \right\|^2 \\ & = p_{\text{page}} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] \right\|^2 \right] \right] + (1 - p_{\text{page}}) \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,2}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,2}^{t+1} \right] \right] \right\|^2 \right] \right] \\ & \quad + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2. \quad (25) \end{aligned}$$

563 Let us consider  $\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] \right\|^2 \right] \right]$ :

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] \right\|^2 \right] \right] \\ & = \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] \right\|^2 \right] \\ & = p_a \left\| h_i^t + \frac{1}{p_a} k_{i,1}^{t+1} - \left( h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right) \right\|^2 \\ & \quad + (1 - p_a) \left\| h_i^t - \left( h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right) \right\|^2 \\ & = \frac{(1 - p_a)^2}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\ & \quad + (1 - p_a) \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\ & = \frac{1 - p_a}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right\|^2. \end{aligned}$$

564 Considering (13) and Assumption 3, we obtain

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,1}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right] \right\|^2 \right] \right] \\ & \leq \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{2(1-p_a)b^2}{p_a p_{\text{page}}^2} \|h_i^t - \nabla f_i(x^t)\|^2. \end{aligned} \quad (26)$$

565 Next, we obtain the bound for  $\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,2}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,2}^{t+1} \right] \right] \right\|^2 \right] \right]$ :

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{i,2}^{t+1} - \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ h_{i,2}^{t+1} \right] \right] \right\|^2 \right] \right] \\ & = p_a \mathbb{E}_B \left[ \left\| h_i^t + \frac{1}{p_a} k_{i,2}^{t+1} - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\ & \quad + (1-p_a) \mathbb{E}_B \left[ \left\| h_i^t - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\ & = p_a \mathbb{E}_B \left[ \left\| \frac{1}{p_a} k_{i,2}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\ & \quad + (1-p_a) \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\ & \stackrel{(14)}{=} \frac{1}{p_a} \mathbb{E}_B \left[ \left\| k_{i,2}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] + \frac{(1-p_a)^2}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\ & \quad + (1-p_a) \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\ & = \frac{1}{p_a} \mathbb{E}_B \left[ \left\| k_{i,2}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] + \frac{1-p_a}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\ & \leq \frac{1}{p_a} \mathbb{E}_B \left[ \left\| k_{i,2}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] + \frac{(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2, \end{aligned} \quad (27)$$

566 where we used Assumption 3. By plugging (26) and (27) into (25), we get

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] \right] \\ & \leq p_{\text{page}} \left( \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{2(1-p_a)b^2}{p_a p_{\text{page}}^2} \|h_i^t - \nabla f_i(x^t)\|^2 \right) \\ & \quad + (1-p_{\text{page}}) \left( \frac{1}{p_a} \mathbb{E}_B \left[ \left\| k_{i,2}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] + \frac{(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 \right) \\ & \quad + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\ & \leq \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{1-p_{\text{page}}}{p_a} \mathbb{E}_B \left[ \left\| k_{i,2}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\ & \quad + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2. \end{aligned}$$

567 From the independence of elements in the mini-batch, we obtain

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] \right] \\ & \leq \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{1-p_{\text{page}}}{p_a} \mathbb{E}_B \left[ \left\| \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\ & \quad + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \end{aligned}$$

$$\begin{aligned}
&= \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{1-p_{\text{page}}}{p_a B^2} \mathbb{E}_B \left[ \sum_{j \in I_i^t} \|(\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\
&\quad + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\
&= \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{1-p_{\text{page}}}{m p_a B} \sum_{j=1}^m \|(\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \\
&\quad + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\
&\leq \frac{2(1-p_a)L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{1-p_{\text{page}}}{m p_a B} \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)\|^2 \\
&\quad + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\
&\leq \left( \frac{2(1-p_a)L_i^2}{p_a} + \frac{(1-p_{\text{page}})L_{\max}^2}{p_a B} \right) \|x^{t+1} - x^t\|^2 \\
&\quad + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2,
\end{aligned}$$

568 where we used Assumption 4. Finally, we prove the last inequality:

$$\begin{aligned}
&\mathbb{E}_B \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|k_i^{t+1}\|^2 \right] \right] \\
&= p_{\text{page}} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\
&\quad + (1-p_{\text{page}}) \mathbb{E}_B \left[ \left\| \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) \right\|^2 \right] \\
&\stackrel{(14)}{=} p_{\text{page}} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\
&\quad + (1-p_{\text{page}}) \mathbb{E}_B \left[ \left\| \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
&\quad + (1-p_{\text{page}}) \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
&\stackrel{(13)}{\leq} 2p_{\text{page}} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2 \\
&\quad + (1-p_{\text{page}}) \mathbb{E}_B \left[ \left\| \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
&\quad + (1-p_{\text{page}}) \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
&\leq 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2
\end{aligned}$$

$$+ (1 - p_{\text{page}}) \mathbb{E}_B \left[ \left\| \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right].$$

569 Using the independence of elements in the mini-batch, we have

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|k_i^{t+1}\|^2 \right] \right] \\ & \leq 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2 \\ & \quad + \frac{1 - p_{\text{page}}}{B^2} \mathbb{E}_B \left[ \sum_{j \in I_i^t} \|(\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\ & = 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2 \\ & \quad + \frac{1 - p_{\text{page}}}{Bm} \sum_{j=1}^m \|(\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \\ & \leq 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2 \\ & \quad + \frac{1 - p_{\text{page}}}{Bm} \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)\|^2 \end{aligned}$$

570 It is left to consider Assumptions 3 and 4 to get

$$\begin{aligned} & \mathbb{E}_B \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|k_i^{t+1}\|^2 \right] \right] \\ & \leq \left( 2L_i^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \|x^{t+1} - x^t\|^2 + \frac{2b^2}{p_{\text{page}}} \|h_i^t - \nabla f_i(x^t)\|^2. \end{aligned}$$

571

□

572 **Theorem 3.** Suppose that Assumptions 1, 2, 3, 4, 7, and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_{\text{page}}p_a}{2-p_a}$ ,  
573 probability  $p_{\text{page}} \in (0, 1]$ ,

$$\begin{aligned} \gamma & \leq \left( L + \left[ \frac{48\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right. \right. \\ & \quad \left. \left. + \frac{16}{np_a^2 p_{\text{page}}} \left( \left( 1 - \frac{p_{\text{aa}}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right]^{1/2} \right)^{-1} \end{aligned}$$

574 and  $g_i^0 = h_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-PAGE) then  $\mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] \leq$   
575  $\frac{2\Delta_0}{\gamma T}$ .

576 *Proof.* Let us fix constants  $\nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 6, Lemma 8,  
577 and the law of total expectation, we obtain

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{\text{aa}})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & \quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \end{aligned}$$

$$\begin{aligned}
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& = \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_{\text{page}}} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \right] \right] \\
& + \nu \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \right] \\
& + \rho \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{page}}} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \left( 2\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \|x^{t+1} - x^t\|^2 + \frac{2b^2}{p_{\text{page}}} \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \nu \mathbb{E} \left( \left( \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} + \frac{(1-p_{\text{page}})L_{\max}^2}{np_a B} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{page}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \|h^t - \nabla f(x^t)\|^2 \right) \\
& + \rho \mathbb{E} \left( \left( \frac{2(1-p_a)\hat{L}^2}{p_a} + \frac{(1-p_{\text{page}})L_{\max}^2}{p_a B} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right)
\end{aligned}$$

578 After rearranging the terms, we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right]
\end{aligned}$$



$$\begin{aligned}
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( 2\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \nu \left( \frac{2(p_a - p_{\text{aa}})\hat{L}^2}{np_a^2} + \frac{(1-p_{\text{page}})L_{\max}^2}{np_a B} \right) - \rho \left( \frac{2(1-p_a)\hat{L}^2}{p_a} + \frac{(1-p_{\text{page}})L_{\max}^2}{p_a B} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left( \gamma + \nu \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\nu(p_a - p_{\text{aa}})b^2}{np_a^2 p_{\text{page}}} \right. \\
& \quad \left. + \rho \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

Due to  $b = \frac{p_{\text{page}} p_a}{2-p_a} \leq p_{\text{page}}$ , one can show that  $\left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \leq 1-b$ . Thus, if we take  $\nu = \frac{\gamma}{b}$ , then

$$\left( \gamma + \nu \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \leq \gamma + \nu(1-b) = \nu,$$

579 therefore

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{\text{aa}})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{\text{aa}})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( 2\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \frac{\gamma}{b} \left( \frac{2(p_a - p_{\text{aa}})\hat{L}^2}{np_a^2} + \frac{(1-p_{\text{page}})L_{\max}^2}{np_a B} \right) - \rho \left( \frac{2(1-p_a)\hat{L}^2}{p_a} + \frac{(1-p_{\text{page}})L_{\max}^2}{p_a B} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{\text{aa}})b}{np_a^2 p_{\text{page}}} \right. \\
& \quad \left. + \rho \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

Next, with the choice of  $b = \frac{p_{\text{page}} p_a}{2-p_a}$ , we ensure that

$$\left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \leq 1-b.$$

If we take  $\rho = \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{\text{aa}})}{np_a^2 p_{\text{page}}}$ , then

$$\left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{\text{aa}})b}{np_a^2 p_{\text{page}}} + \rho \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \leq \rho,$$

580 therefore

$$\begin{aligned}
& \mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
& - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left(2\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right)\right) \\
& - \frac{\gamma}{bnp_a} \left(2\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \\
& - \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^3 p_{\text{page}}} + \frac{2\gamma\left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2 p_{\text{page}}}\right) \left(2(1-p_a)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^3 p_{\text{page}}} + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
\end{aligned}$$

Let us simplify the inequality. First, due to  $b \geq \frac{p_{\text{page}} p_a}{2}$ , we have

$$\frac{\gamma}{bnp_a} \left(2\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \leq \frac{4\gamma}{np_a^2 p_{\text{page}}} \left(\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right).$$

581 Second, due to  $b \leq p_a p_{\text{page}}$  and  $p_{aa} \leq p_a^2$ , we get

$$\begin{aligned}
& \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^3 p_{\text{page}}} + \frac{2\gamma\left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2 p_{\text{page}}}\right) \left(2(1-p_a)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \\
& \leq \left(\frac{8\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma\left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2 p_{\text{page}}}\right) \left(2\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \\
& \leq \frac{16\gamma\omega(2\omega+1)}{np_a^2} \left(\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \\
& + \frac{4\gamma\left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2 p_{\text{page}}} \left(\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \\
& \leq \frac{16\gamma\omega(2\omega+1)}{np_a^2} \left(\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right) \\
& + \frac{4\gamma}{np_a^2 p_{\text{page}}} \left(\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\text{max}}^2}{B}\right).
\end{aligned}$$

582 Combining all bounds together, we obtain the following simplified inequality:

$$\begin{aligned}
& \mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2]
\end{aligned}$$

$$\begin{aligned}
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{24\gamma\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \frac{8\gamma}{np_a^2 p_{\text{page}}} \left( \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

583 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

584 It is left to apply Lemma 3 with

$$\begin{aligned}
\Psi^t &= \frac{(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{1}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right]
\end{aligned}$$

585 to conclude the proof.  $\square$

586 **Corollary 1.** Let the assumptions from Theorem 3 hold and  $p_{\text{page}} = B/(m+B)$ . Then DASHA-PP-PAGE  
587 needs

$$\begin{aligned}
T &:= \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) \right. \right. \\
& \quad \left. \left. + \frac{1}{p_a} \sqrt{\frac{m}{n}} \left( \frac{\hat{L}}{\sqrt{B}} + \frac{L_{\max}}{B} \right) \right] \right)
\end{aligned} \tag{6}$$

588 communication rounds to get an  $\varepsilon$ -solution and the expected number of gradient calculations per  
589 node equals  $\mathcal{O}(m + BT)$ .

590 *Proof.* In the view of Theorem 3, it is enough to do

$$T := \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \sqrt{\frac{\omega^2}{np_a^2} \left( \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right)} + \frac{1}{np_a^2 p_{\text{page}}} \left( \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right] \right)$$

591 steps to get  $\varepsilon$ -solution. Using the choice of  $p_{\text{mega}}$  and the definition of  $\mathbb{1}_{p_a}$ , we can get (6).

592 Note that the expected number of gradients calculations at each communication round equals  $p_{\text{mega}}m +$   
593  $(1 - p_{\text{mega}})B = \frac{2mB}{m+B} \leq 2B$ .  $\square$

594 **Corollary 2.** Suppose that assumptions of Corollary 1 hold,  $B \leq \min \left\{ \frac{1}{p_a} \sqrt{\frac{m}{n}}, \frac{L_{\max}^2}{\frac{1}{p_a} \hat{L}^2} \right\}$ <sup>6</sup>, and we  
 595 use the unbiased compressor RandK with  $K = \Theta(Bd/\sqrt{m})$ . Then the communication complexity of  
 596 Algorithm 1 is

$$\mathcal{O} \left( d + \frac{L_{\max} \Delta_0 d}{p_a \varepsilon \sqrt{n}} \right), \quad (7)$$

597 and the expected number of gradient calculations per node equals

$$\mathcal{O} \left( m + \frac{L_{\max} \Delta_0 \sqrt{m}}{p_a \varepsilon \sqrt{n}} \right). \quad (8)$$

598 *Proof.* The communication complexity equals

$$\mathcal{O}(d + KT) = \mathcal{O} \left( d + \frac{\Delta_0}{\varepsilon} \left[ KL + K \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + K \frac{1}{p_a} \sqrt{\frac{m}{n}} \left( \frac{\mathbb{1}_{p_a} \hat{L}}{\sqrt{B}} + \frac{L_{\max}}{B} \right) \right] \right).$$

599 Since  $B \leq \frac{L_{\max}^2}{\frac{1}{p_a} \hat{L}^2}$ , we have  $\frac{\mathbb{1}_{p_a} \hat{L}}{\sqrt{B}} + \frac{L_{\max}}{B} \leq \frac{2L_{\max}}{B}$  and

$$\mathcal{O}(d + KT) = \mathcal{O} \left( d + \frac{\Delta_0}{\varepsilon} \left[ KL + K \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + K \frac{1}{p_a} \sqrt{\frac{m}{n}} \frac{L_{\max}}{B} \right] \right).$$

600 Note that  $K = \Theta \left( \frac{Bd}{\sqrt{m}} \right) = \mathcal{O} \left( \frac{d}{p_a \sqrt{n}} \right)$  and  $\omega + 1 = \frac{d}{K}$  due to Theorem 6, thus

$$\begin{aligned} \mathcal{O}(d + KT) &= \mathcal{O} \left( d + \frac{\Delta_0}{\varepsilon} \left[ \frac{d}{p_a \sqrt{n}} L + \frac{d}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + \frac{d}{p_a \sqrt{n}} L_{\max} \right] \right) \\ &= \mathcal{O} \left( d + \frac{L_{\max} \Delta_0 d}{p_a \varepsilon \sqrt{n}} \right). \end{aligned}$$

601 Using the same reasoning, the expected number of gradient calculations per node equals

$$\begin{aligned} \mathcal{O}(m + BT) &= \mathcal{O} \left( m + \frac{\Delta_0}{\varepsilon} \left[ BL + B \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + B \frac{1}{p_a} \sqrt{\frac{m}{n}} \left( \frac{\mathbb{1}_{p_a} \hat{L}}{\sqrt{B}} + \frac{L_{\max}}{B} \right) \right] \right) \\ &= \mathcal{O} \left( m + \frac{\Delta_0}{\varepsilon} \left[ BL + B \frac{d}{K p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + B \frac{1}{p_a} \sqrt{\frac{m}{n}} \frac{L_{\max}}{B} \right] \right) \\ &= \mathcal{O} \left( m + \frac{\Delta_0}{\varepsilon} \left[ \frac{1}{p_a} \sqrt{\frac{m}{n}} L + \frac{\sqrt{m}}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + \frac{1}{p_a} \sqrt{\frac{m}{n}} L_{\max} \right] \right) \\ &= \mathcal{O} \left( m + \frac{L_{\max} \Delta_0 \sqrt{m}}{p_a \varepsilon \sqrt{n}} \right). \end{aligned}$$

602 □

## 603 D.5 Proof for DASHA-PP-FINITE-MVR

604 **Lemma 9.** Suppose that Assumptions 3, 4, and 8 hold. For  $h_i^{t+1}$ ,  $h_{ij}^{t+1}$  and  $k_i^{t+1}$  from Algorithm 1  
 605 (DASHA-PP-FINITE-MVR) we have

1.

$$\begin{aligned} &\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\ &\leq \left( \frac{2L_{\max}^2}{np_a B} + \frac{2(p_a - p_{aa}) \hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \end{aligned}$$

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<sup>6</sup>If  $\mathbb{1}_{p_a} = 0$ , then  $\frac{L_{\max}^2}{\frac{1}{p_a} \hat{L}^2} = +\infty$

$$\begin{aligned}
& + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \frac{2b^2}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

2.

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& \leq \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)L_i^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \\
& + \frac{2b^2}{p_a B m} \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n].
\end{aligned}$$

3.

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{2 \left( 1 - \frac{p_a B}{m} \right) L_{\max}^2}{\frac{p_a B}{m}} \|x^{t+1} - x^t\|^2 \\
& + \left( \frac{2 \left( 1 - \frac{p_a B}{m} \right) b^2}{\frac{p_a B}{m}} + (1-b)^2 \right) \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2, \quad \forall i \in [n], \forall j \in [m].
\end{aligned}$$

4.

$$\begin{aligned}
& \mathbb{E}_B \left[ \|k_i^{t+1}\|^2 \right] \\
& \leq \left( \frac{2L_{\max}^2}{B} + 2L_i^2 \right) \|x^{t+1} - x^t\|^2 \\
& + \frac{2b^2}{B m} \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n].
\end{aligned}$$

606 *Proof.* We start by proving the first inequality. Note that

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} [h_i^{t+1}] \right] \\
& = p_a \left( h_i^t + \frac{1}{p_a} \mathbb{E}_B [k_i^{t+1}] \right) + (1-p_a)h_i^t \\
& = h_i^t + \frac{1}{m} \sum_{j=1}^m \frac{B}{m} \cdot \frac{m}{B} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))) + \left( 1 - \frac{B}{m} \right) \cdot 0 \\
& = \nabla f_i(x^{t+1}) + (1-b)(h_i^t - \nabla f_i(x^t)),
\end{aligned}$$

607 thus

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \stackrel{(14)}{=} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \mathbb{E}_B [\mathbb{E}_{p_a} [h^{t+1}]]\|^2 \right] \right] + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

608 We can use Lemma 1 with  $r_i = h_i^t$  and  $s_i = k_i^{t+1}$  to obtain

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_B \left[ \|k_i^{t+1} - \mathbb{E}_B [k_i^{t+1}]\|^2 \right] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\mathbb{E}_B [k_i^{t+1}]\|^2
\end{aligned}$$

$$\begin{aligned}
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \\
& = \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_B \left[ \left\| \frac{1}{m} \sum_{j=1}^m k_{ij}^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

609 Next, we again use Lemma 1 with  $r_i = 0$ ,  $s_i = \nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))$ ,  
610  $p_a = \frac{B}{m}$ , and  $p_{aa} = \frac{B(B-1)}{m(m-1)}$ :

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \left( \frac{m-B}{Bm(m-1)} \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \right) \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \\
& \leq \frac{1}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \\
& \stackrel{(13)}{\leq} \frac{2}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)\|^2 + \frac{2b^2}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& + \frac{2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

611 Due to Assumptions 3 and 4, we have

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \leq \left( \frac{2L_{\max}^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \\
& + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \frac{2b^2}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

612 Let us get the bound for the second inequality:

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& \stackrel{(14)}{=} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - (\nabla f_i(x^{t+1}) + (1-b)(h_i^t - \nabla f_i(x^t)))\|^2 \right] \right] \\
& + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2
\end{aligned}$$

$$\begin{aligned}
&= p_a \mathbb{E}_B \left[ \left\| h_i^t + \frac{1}{p_a} k_i^{t+1} - (\nabla f_i(x^{t+1}) + (1-b)(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] \\
&\quad + (1-p_a) \left\| h_i^t - (\nabla f_i(x^{t+1}) + (1-b)(h_i^t - \nabla f_i(x^t))) \right\|^2 \\
&\quad + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\
&\stackrel{(14)}{=} \frac{1}{p_a} \mathbb{E}_B \left[ \left\| k_i^{t+1} - \mathbb{E}_B[k_i^{t+1}] \right\|^2 \right] \\
&\quad + \frac{1-p_a}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
&\quad + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2.
\end{aligned}$$

613 Let us use Lemma 1 with  $r_i = 0$ ,  $s_i = \nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))$ ,  $p_a = \frac{B}{m}$ , and

614  $p_{aa} = \frac{B(B-1)}{m(m-1)}$ :

$$\begin{aligned}
&\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] \\
&\leq \frac{1}{p_a} \left( \frac{m-B}{Bm(m-1)} \sum_{j=1}^m \left\| \nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t)) \right\|^2 \right) \\
&\quad + \frac{1-p_a}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
&\quad + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\
&\leq \frac{1}{p_a B m} \sum_{j=1}^m \left\| \nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t)) \right\|^2 \\
&\quad + \frac{1-p_a}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
&\quad + (1-b)^2 \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\
&\stackrel{(13)}{\leq} \frac{2}{p_a B m} \sum_{j=1}^m \left\| \nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) \right\|^2 + \frac{2(1-p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\
&\quad + \frac{2b^2}{p_a B m} \sum_{j=1}^m \left\| h_{ij}^t - \nabla f_{ij}(x^t) \right\|^2 + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\
&\leq \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)L_i^2}{p_a} \right) \left\| x^{t+1} - x^t \right\|^2 \\
&\quad + \frac{2b^2}{p_a B m} \sum_{j=1}^m \left\| h_{ij}^t - \nabla f_{ij}(x^t) \right\|^2 + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \left\| h_i^t - \nabla f_i(x^t) \right\|^2,
\end{aligned}$$

615 where we used Assumptions 3 and 4. We continue the proof by considering

616  $\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1}) \right\|^2 \right] \right]$ :

$$\begin{aligned}
&\mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1}) \right\|^2 \right] \right] \\
&\stackrel{(14)}{=} \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \left\| h_{ij}^{t+1} - (\nabla f_{ij}(x^{t+1}) + (1-b)(h_{ij}^t - \nabla f_{ij}(x^t))) \right\|^2 \right] \right] \\
&\quad + (1-b)^2 \left\| h_{ij}^t - \nabla f_{ij}(x^t) \right\|^2 \\
&= \frac{p_a B}{m} \mathbb{E}_B \left[ \left\| h_{ij}^t + \frac{m}{B p_a} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))) - (\nabla f_{ij}(x^{t+1}) + (1-b)(h_{ij}^t - \nabla f_{ij}(x^t))) \right\|^2 \right] \\
&\quad + \left( 1 - \frac{p_a B}{m} \right) \left\| h_{ij}^t - (\nabla f_{ij}(x^{t+1}) + (1-b)(h_{ij}^t - \nabla f_{ij}(x^t))) \right\|^2
\end{aligned}$$

$$\begin{aligned}
& + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& = \frac{\left(1 - \frac{p_a B}{m}\right)^2}{\frac{p_a B}{m}} \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
& \quad + \left(1 - \frac{p_a B}{m}\right) \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
& \quad + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& = \frac{\left(1 - \frac{p_a B}{m}\right)}{\frac{p_a B}{m}} \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
& \quad + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& \stackrel{(13)}{\leq} \frac{2\left(1 - \frac{p_a B}{m}\right)}{\frac{p_a B}{m}} \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)\|^2 + \left(\frac{2\left(1 - \frac{p_a B}{m}\right)b^2}{\frac{p_a B}{m}} + (1-b)^2\right) \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2.
\end{aligned}$$

617 It is left to consider Assumption 4:

$$\begin{aligned}
& \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{2\left(1 - \frac{p_a B}{m}\right) L_{\max}^2}{\frac{p_a B}{m}} \|x^{t+1} - x^t\|^2 + \left(\frac{2\left(1 - \frac{p_a B}{m}\right)b^2}{\frac{p_a B}{m}} + (1-b)^2\right) \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2.
\end{aligned}$$

618 Finally, we obtain the bound for the last inequality of the lemma:

$$\begin{aligned}
& \mathbb{E}_B \left[ \|k_i^{t+1}\|^2 \right] \\
& \stackrel{(14)}{=} \mathbb{E}_B \left[ \|k_i^{t+1} - \mathbb{E}_B[k_i^{t+1}]\|^2 \right] \\
& \quad + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2.
\end{aligned}$$

619 Using Lemma 1, we get

$$\begin{aligned}
& \mathbb{E}_B \left[ \|k_i^{t+1}\|^2 \right] \\
& \leq \frac{m-B}{Bm(m-1)} \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
& \quad + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \leq \frac{1}{Bm} \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
& \quad + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \stackrel{(13)}{\leq} \frac{2}{Bm} \sum_{j=1}^m \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)\|^2 + 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
& \quad + \frac{2b^2}{Bm} \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& \leq \left( \frac{2L_{\max}^2}{B} + 2L_i^2 \right) \|x^{t+1} - x^t\|^2 \\
& \quad + \frac{2b^2}{Bm} \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2,
\end{aligned}$$



620 where we used Assumptions 3 and 4. □

**Theorem 7.** Suppose that Assumptions 1, 2, 3, 4, 7, and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{\frac{p_a B}{m}}{2 - \frac{p_a B}{m}}$ ,

$$\gamma \leq \left( L + \sqrt{\frac{148\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{L_{\max}^2}{B} \right) + \frac{72m}{np_a^2 B} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{L_{\max}^2}{B} \right)} \right)^{-1},$$

621  $g_i^0 = h_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  and  $h_{ij}^0 = \nabla f_{ij}(x^0)$  for all  $i \in [n], j \in [m]$  in Algorithm 1  
 622 (DASHA-PP-FINITE-MVR) then  $\mathbb{E} [\|\nabla f(\hat{x}^T)\|^2] \leq \frac{2\Delta_0}{\gamma T}$ .

623 *Proof.* Let us fix constants  $\nu, \rho, \delta \in [0, \infty)$  that we will define later. Considering Lemma 6, Lemma 9,  
 624 and the law of total expectation, we obtain

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & + \delta \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \\ & + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & + \delta \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\ & = \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \mathbb{E}_B \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \right] \\ & + \nu \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] \right] \right] \\ & + \rho \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\ & + \delta \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \right] \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \end{aligned}$$

$$\begin{aligned}
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \|x^{t+1} - x^t\|^2 + \frac{2b^2}{Bmn} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + \frac{2b^2}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \nu \mathbb{E} \left( \left( \frac{2L_{\max}^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \frac{2b^2}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right. \\
& \quad \left. + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \right) \\
& + \rho \mathbb{E} \left( \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \frac{2b^2}{p_a B n m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right) \\
& + \delta \mathbb{E} \left( \frac{2 \left(1 - \frac{p_a B}{m}\right) L_{\max}^2}{\frac{p_a B}{m}} \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \left( \frac{2 \left(1 - \frac{p_a B}{m}\right) b^2}{\frac{p_a B}{m}} + (1-b)^2 \right) \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right).
\end{aligned}$$

Due to  $b = \frac{\frac{p_a B}{m}}{2 - \frac{p_a B}{m}} \leq \frac{p_a}{2 - p_a}$ , we have

$$\left( \frac{2 \left(1 - \frac{p_a B}{m}\right) b^2}{\frac{p_a B}{m}} + (1-b)^2 \right) \leq 1 - b$$

and

$$\left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \leq 1 - b.$$

625 Moreover, we consider that  $1 - \frac{p_a B}{m} \leq 1$ , therefore

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \delta \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \|x^{t+1} - x^t\|^2 + \frac{2b^2}{Bmn} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + \frac{2b^2}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \nu \mathbb{E} \left( \left( \frac{2L_{\max}^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \frac{2b^2}{n^2 p_a B m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
& \quad \left. + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \right) \\
& + \rho \mathbb{E} \left( \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad + \frac{2b^2}{p_a B n m} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + (1-b) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \left. \right) \\
& + \delta \mathbb{E} \left( \frac{2mL_{\max}^2}{p_a B} \|x^{t+1} - x^t\|^2 + (1-b) \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right).
\end{aligned}$$

626 After rearranging the terms, we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \delta \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \right. \\
& \quad \left. - \nu \left( \frac{2L_{\max}^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) - \delta \frac{2mL_{\max}^2}{p_a B} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + (\gamma + \nu(1-b)^2) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\nu(p_a - p_{aa})b^2}{np_a^2} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{2\nu b^2}{np_a B} + \frac{2\rho b^2}{p_a B} + \delta(1-b) \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right].
\end{aligned}$$

627 Thus, if we take  $\nu = \frac{\gamma}{b}$ , then  $\gamma + \nu(1-b)^2 \leq \nu$  and

$$\mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right]$$

$$\begin{aligned}
& + \frac{\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \delta \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{2\gamma L_{\max}^2}{bnp_a B} + \frac{2\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) - \rho \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) - \delta \frac{2mL_{\max}^2}{p_a B} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})b}{np_a^2} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{2\gamma b}{np_a B} + \frac{2\rho b^2}{p_a B} + \delta(1-b) \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right].
\end{aligned}$$

Next, if we take  $\rho = \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}$ , then

$$\left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})b}{np_a^2} + \rho(1-b) \right) = \rho,$$

628 therefore

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \delta \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \right. \\
& \quad - \left( \frac{2\gamma L_{\max}^2}{bnp_a B} + \frac{2\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) - \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \\
& \quad \left. - \delta \frac{2mL_{\max}^2}{p_a B} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2]
\end{aligned}$$

$$\begin{aligned}
& + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{2\gamma b}{np_a B} + \frac{16b^3\gamma\omega(2\omega+1)}{np_a^3 B} + \frac{4b^2\gamma(p_a - p_{aa})}{nBp_a^3} + \delta(1-b) \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right].
\end{aligned}$$

629 Due to  $b \leq p_a$  and  $\frac{p_a - p_{aa}}{p_a} \leq 1$ , we have

$$\begin{aligned}
& \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{2\gamma b}{np_a B} + \frac{16b^3\gamma\omega(2\omega+1)}{np_a^3 B} + \frac{4b^2\gamma(p_a - p_{aa})}{nBp_a^3} \\
& \leq \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{2\gamma b}{np_a B} + \frac{16b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{4\gamma b}{np_a B} \\
& = \frac{24b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma b}{np_a B}.
\end{aligned}$$

630 Let us take  $\delta = \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B}$ . Thus

$$\left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{2\gamma b}{np_a B} + \frac{16b^3\gamma\omega(2\omega+1)}{np_a^3 B} + \frac{4b^2\gamma(p_a - p_{aa})}{nBp_a^3} + \delta(1-b) \right) \leq \delta$$

631 and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{2\gamma L_{\max}^2}{bnp_a B} + \frac{2\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) - \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \right. \\
& \quad \left. - \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \frac{2mL_{\max}^2}{p_a B} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right].
\end{aligned}$$

632 Let us simplify the term near  $\mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right]$ . Due to  $b \leq p_a$ ,  $\frac{p_a - p_{aa}}{p_a} \leq 1$ , and  $1 - p_a \leq 1$ , we  
633 have

$$\begin{aligned}
& \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \\
& + \left( \frac{2\gamma L_{\max}^2}{bnp_a B} + \frac{2\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) \\
& + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \frac{2mL_{\max}^2}{p_a B} \\
& \leq \frac{12\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \\
& + \left( \frac{6\gamma L_{\max}^2}{bnp_a B} + \frac{6\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \frac{2mL_{\max}^2}{p_a B}
\end{aligned}$$

634 Considering that  $b \leq \frac{p_a B}{m}$  and  $b \geq \frac{p_a B}{2m}$ , we obtain

$$\begin{aligned}
& \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) \\
& + \left( \frac{2\gamma L_{\max}^2}{bnp_a B} + \frac{2\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) \\
& + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \left( \frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \frac{2mL_{\max}^2}{p_a B} \\
& \leq \frac{36\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) + \left( \frac{18\gamma L_{\max}^2}{bnp_a B} + \frac{6\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right) \\
& \leq \frac{36\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) + \left( \frac{36m\gamma L_{\max}^2}{np_a^2 B^2} + \frac{12m\gamma(p_a - p_{aa})\hat{L}^2}{Bnp_a^3} \right).
\end{aligned}$$

635 All in all, we have

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{36\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right) - \left( \frac{36m\gamma L_{\max}^2}{np_a^2 B^2} + \frac{12m\gamma(p_a - p_{aa})\hat{L}^2}{Bnp_a^3} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right].
\end{aligned}$$

636 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{24b\gamma\omega(2\omega+1)}{np_a^2 B} + \frac{6\gamma}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right].
\end{aligned}$$

637 It is left to apply Lemma 3 with

$$\begin{aligned}
\Psi^t &= \frac{(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{1}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{8b\omega(2\omega+1)}{np_a^2} + \frac{2(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{24b\omega(2\omega+1)}{np_a^2 B} + \frac{6}{np_a B} \right) \mathbb{E} \left[ \frac{1}{nm} \sum_{i=1}^n \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \right]
\end{aligned}$$

638 to conclude the proof.  $\square$

## 639 D.6 Proof for DASHA-PP-MVR

640 Let us denote  $\nabla f_i(x^{t+1}; \xi_i^{t+1}) := \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1})$ .

641 **Lemma 10.** Suppose that Assumptions 3, 5, 6 and 8 hold. For  $h_i^{t+1}$  and  $k_i^{t+1}$  from Algorithm 1  
642 (DASHA-PP-MVR) we have

1.

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{2b^2\sigma^2}{np_a B} + \left( \frac{2(1-b)^2 L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa}) \hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \\
& \quad + \frac{2(p_a - p_{aa}) b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

2.

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{2b^2\sigma^2}{p_a B} + \left( \frac{2(1-b)^2 L_\sigma^2}{p_a B} + \frac{2(1-p_a) L_i^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \\
& \quad + \left( \frac{2(1-p_a) b^2}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n].
\end{aligned}$$

3.

$$\mathbb{E}_k \left[ \|k_i^{t+1}\|^2 \right] \leq \frac{2b^2\sigma^2}{B} + \left( \frac{2(1-b)^2 L_\sigma^2}{B} + 2L_i^2 \right) \|x^{t+1} - x^t\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n].$$

643 *Proof.* First, let us proof the bound for  $\mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right]$ :

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& = \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \mathbb{E}_k [\mathbb{E}_{p_a} [h^{t+1}]]\|^2 \right] \right] + \|\mathbb{E}_k [\mathbb{E}_{p_a} [h^{t+1}]] - \nabla f(x^{t+1})\|^2.
\end{aligned}$$

644 Using

$$\mathbb{E}_k [\mathbb{E}_{p_a} [h_i^{t+1}]] = h_i^t + \mathbb{E}_k [k_i^{t+1}] = h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))$$

645 and (14), we have

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& = \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \mathbb{E}_k [\mathbb{E}_{p_a} [h^{t+1}]]\|^2 \right] \right] + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

646 We can use Lemma 1 with  $r_i = h_i^t$  and  $s_i = k_i^{t+1}$  to obtain

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \|k_i^{t+1} - \mathbb{E}_k [k_i^{t+1}]\|^2 \right] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\mathbb{E}_k [k_i^{t+1}]\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \\
& = \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - b(h_i^t - \nabla f_i(x^t; \xi_i^{t+1})) \right. \\
& \quad \left. - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)))\|^2 \right] \\
& \quad + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \quad + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \\
& \stackrel{(13)}{\leq} \frac{2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \|b(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1}))\|^2 \right]
\end{aligned}$$



$$\begin{aligned}
& + \frac{2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \left\| (1-b) (\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
& + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2 \\
& = \frac{2b^2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1}) \right\|^2 \right] \\
& + \frac{2(1-b)^2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
& + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2. \\
& = \frac{2b^2}{n^2 p_a B^2} \sum_{i=1}^n \sum_{j=1}^B \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^{t+1}) \right\|^2 \right] \\
& + \frac{2(1-b)^2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
& + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2.
\end{aligned}$$

647 In the last equality, we use the independence of elements in the mini-batches. Due to Assumption 5,  
648 we get

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] \right] \\
& \leq \frac{2b^2 \sigma^2}{n p_a B} \\
& + \frac{2(1-b)^2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) \right\|^2 \\
& + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2 \\
& \stackrel{(13)}{\leq} \frac{2b^2 \sigma^2}{n p_a B} \\
& + \frac{2(1-b)^2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& + \frac{2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \\
& + (1-b)^2 \left\| h^t - \nabla f(x^t) \right\|^2. \\
& = \frac{2b^2 \sigma^2}{n p_a B} \\
& + \frac{2(1-b)^2}{n^2 p_a B^2} \sum_{i=1}^n \sum_{j=1}^B \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^t; \xi_{ij}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + \frac{2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \\
& + (1-b)^2 \|h^t - \nabla f(x^t)\|^2,
\end{aligned}$$

649 where we use the independence of elements in the mini-batches. Using Assumptions 3 and 6, we  
650 obtain

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{2b^2 \sigma^2}{np_a B} + \left( \frac{2(1-b)^2 L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa}) \widehat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \\
& \quad + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

651 Now, we prove the second inequality:

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& = \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \mathbb{E}_k [\mathbb{E}_{p_a} [h_i^{t+1}]]\|^2 \right] \right] \\
& \quad + \|\mathbb{E}_k [\mathbb{E}_{p_a} [h_i^{t+1}]] - \nabla f_i(x^{t+1})\|^2 \\
& = \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)))\|^2 \right] \right] \\
& \quad + \|h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)) - \nabla f_i(x^{t+1})\|^2 \\
& = \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)))\|^2 \right] \right] \\
& \quad + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& = p_a \mathbb{E}_k \left[ \left\| h_i^t + \frac{1}{p_a} k_i^{t+1} - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] \\
& \quad + (1-p_a) \|h_i^t - (h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)))\|^2 \\
& \quad + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& = p_a \mathbb{E}_k \left[ \left\| \frac{1}{p_a} k_i^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] \\
& \quad + (1-p_a) \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \quad + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& \stackrel{(14)}{=} \frac{1}{p_a} \mathbb{E}_k \left[ \left\| k_i^{t+1} - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] \\
& \quad + \frac{(1-p_a)^2}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \quad + (1-p_a) \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \quad + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& = \frac{1}{p_a} \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - b(h_i^t - \nabla f_i(x^t; \xi_i^{t+1})) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))) \right\|^2 \right] \\
& \quad + \frac{1-p_a}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \quad + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& = \frac{1}{p_a} \mathbb{E}_k \left[ \left\| b(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1})) + (1-b)(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))) \right\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + \frac{1-p_a}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2 \\
& \stackrel{(13)}{\leq} \frac{2b^2}{p_a} \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \frac{2(1-b)^2}{p_a} \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\
& + \frac{1-p_a}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

652 Considering the independence of elements in the mini-batch, we obtain

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& = \frac{2b^2}{p_a B^2} \sum_{j=1}^B \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \frac{2(1-b)^2}{p_a B^2} \sum_{j=1}^B \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^t; \xi_{ij}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\
& + \frac{1-p_a}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& + (1-b)^2 \|h_i^t - \nabla f_i(x^t)\|^2. \\
& \stackrel{(13)}{\leq} \frac{2b^2}{p_a B^2} \sum_{j=1}^B \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^{t+1})\|^2 \right] \\
& + \frac{2(1-b)^2}{p_a B^2} \sum_{j=1}^B \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^t; \xi_{ij}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\
& + \frac{2(1-p_a)}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2
\end{aligned}$$

653 Next, we use Assumptions 3, 6, 5, to get

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\
& \leq \frac{2b^2\sigma^2}{p_a B} + \left( \frac{2(1-b)^2 L_\sigma^2}{p_a B} + \frac{2(1-p_a) L_i^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \\
& + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

654 It is left to prove the bound for  $\mathbb{E}_k \left[ \|k_i^{t+1}\|^2 \right]$ :

$$\begin{aligned}
& \mathbb{E}_k \left[ \|k_i^{t+1}\|^2 \right] \\
& = \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - b(h_i^t - \nabla f_i(x^t; \xi_i^{t+1}))\|^2 \right] \\
& \stackrel{(14)}{=} \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - b(h_i^t - \nabla f_i(x^t; \xi_i^{t+1})) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)))\|^2 \right] \\
& + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& = \mathbb{E}_k \left[ \|b(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1})) + (1-b)(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)))\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
& \stackrel{(13)}{\leq} 2b^2 \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1})\|^2 \right] \\
& + 2(1-b)^2 \mathbb{E}_k \left[ \|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\
& + 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

655 Using Assumptions 3, 6, 5 and the independence of elements in the mini-batch, we get

$$\begin{aligned}
& \mathbb{E}_k \left[ \|k_i^{t+1}\|^2 \right] \\
& \leq \frac{2b^2 \sigma^2}{B} + \left( \frac{2(1-b)^2 L_\sigma^2}{B} + 2L_i^2 \right) \|x^{t+1} - x^t\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

656

□

657 **Theorem 4.** Suppose that Assumptions 1, 2, 3, 5, 6, 7 and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  
658  $b \in \left(0, \frac{p_a}{2-p_a}\right]$ ,

$$\begin{aligned}
\gamma \leq & \left( L + \left[ \frac{48\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1-b)^2 L_\sigma^2}{B} \right) \right. \right. \\
& \left. \left. + \frac{12}{np_a b} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1-b)^2 L_\sigma^2}{B} \right) \right]^{1/2} \right)^{-1},
\end{aligned}$$

659 and  $g_i^0 = h_i^0$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-MVR). Then

$$\begin{aligned}
\mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] & \leq \frac{1}{T} \left[ \frac{2\Delta_0}{\gamma} + \frac{2}{b} \|h^0 - \nabla f(x^0)\|^2 \right. \\
& + \left( \frac{32b\omega(2\omega+1)}{np_a^2} + \frac{4 \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_a} \right) \left( \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \\
& \left. + \left( \frac{48b^2\omega(2\omega+1)}{p_a^2} + \frac{12b}{p_a} \right) \frac{\sigma^2}{nB} \right].
\end{aligned}$$

660 *Proof.* Let us fix constants  $\nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 6, Lemma 10,  
661 and the law of total expectation, we obtain

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& = \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \mathbb{E}_k \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \right] \\
& + \nu \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\
& + \rho \mathbb{E} \left[ \mathbb{E}_B \left[ \mathbb{E}_{p_a} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\
\leq & \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \frac{2b^2\sigma^2}{B} + \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\hat{L}^2 \right) \|x^{t+1} - x^t\|^2 + 2b^2 \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \nu \mathbb{E} \left( \frac{2b^2\sigma^2}{np_a B} + \left( \frac{2(1-b)^2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \right) \\
& + \rho \mathbb{E} \left( \frac{2b^2\sigma^2}{p_a B} + \left( \frac{2(1-b)^2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right).
\end{aligned}$$

662 After rearranging the terms, we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\hat{L}^2 \right) \right. \\
& \quad \left. - \nu \left( \frac{2(1-b)^2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) - \rho \left( \frac{2(1-b)^2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \left( \gamma + \nu(1-b)^2 \right) \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\nu(p_a - p_{aa})b^2}{np_a^2} + \rho \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \nu \frac{2b^2}{np_a} + \rho \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

663 By taking  $\nu = \frac{\gamma}{b}$ , one can show that  $(\gamma + \nu(1-b)^2) \leq \nu$ , and

$$\begin{aligned}
& \mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
& - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left(\frac{2(1-b)^2 L_\sigma^2}{B} + 2\hat{L}^2\right)\right. \\
& \quad \left. - \frac{\gamma}{b} \left(\frac{2(1-b)^2 L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2}\right) - \rho \left(\frac{2(1-b)^2 L_\sigma^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a}\right)\right] \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] \\
& + \left(\frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})b}{np_a^2} + \rho \left(\frac{2(1-p_a)b^2}{p_a} + (1-b)^2\right)\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\
& + \left(\frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b}{np_a} + \rho \frac{2b^2}{p_a}\right) \frac{\sigma^2}{B}.
\end{aligned}$$

664 Note that  $b \leq \frac{p_a}{2-p_a}$ , thus

$$\begin{aligned}
& \left(\frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})b}{np_a^2} + \rho \left(\frac{2(1-p_a)b^2}{p_a} + (1-b)^2\right)\right) \\
& \leq \left(\frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})b}{np_a^2} + \rho(1-b)\right).
\end{aligned}$$

665 And if we take  $\rho = \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}$ , then

$$\left(\frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})b}{np_a^2} + \rho(1-b)\right) \leq \rho,$$

666 and

$$\begin{aligned}
& \mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
& - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega(2\omega+1)}{np_a^2} \left(\frac{2(1-b)^2 L_\sigma^2}{B} + 2\hat{L}^2\right)\right. \\
& \quad \left. - \frac{\gamma}{np_a b} \left(\frac{2(1-b)^2 L_\sigma^2}{B} + 2\left(1 - \frac{p_{aa}}{p_a}\right)\hat{L}^2\right)\right)
\end{aligned}$$

$$\begin{aligned}
& - \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^3} + \frac{2\gamma(1-\frac{p_{aa}}{p_a})}{np_a^2} \right) \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2(1-p_a)\widehat{L}^2 \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b}{np_a} + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

667 Let us simplify the inequality. First, due to  $b \leq p_a$  and  $(1-p_a) \leq (1-\frac{p_{aa}}{p_a})$ , we have

$$\begin{aligned}
& \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^3} + \frac{2\gamma(1-\frac{p_{aa}}{p_a})}{np_a^2} \right) \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2(1-p_a)\widehat{L}^2 \right) \\
& = \frac{8b\gamma\omega(2\omega+1)}{np_a^3} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2(1-p_a)\widehat{L}^2 \right) \\
& \quad + \frac{2\gamma(1-\frac{p_{aa}}{p_a})}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2(1-p_a)\widehat{L}^2 \right) \\
& \leq \frac{8\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \\
& \quad + \frac{2\gamma}{np_a b} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2 \left( 1 - \frac{p_{aa}}{p_a} \right) \widehat{L}^2 \right),
\end{aligned}$$

668 therefore

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& \quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& \quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{12\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \right. \\
& \quad \left. - \frac{3\gamma}{np_a b} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2 \left( 1 - \frac{p_{aa}}{p_a} \right) \widehat{L}^2 \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& \quad + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& \quad + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b}{np_a} + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B} \\
& = \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& \quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& \quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{24\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{(1-b)^2L_\sigma^2}{B} + \widehat{L}^2 \right) \right)
\end{aligned}$$

$$\begin{aligned}
& - \frac{6\gamma}{np_a b} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2 \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{8b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma b}{np_a} + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

669 Also, we can simplify the last term:

$$\begin{aligned}
& \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \\
& = \frac{16b^3\gamma\omega(2\omega+1)}{np_a^3} + \frac{4b^2\gamma \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2} \\
& \leq \frac{16b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{4b\gamma}{np_a},
\end{aligned}$$

670 thus

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{24\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
& \quad \left. - \frac{6\gamma}{np_a b} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2 \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{24b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{6\gamma b}{np_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

671 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right]
\end{aligned}$$



$$+ \left( \frac{24b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{6\gamma b}{np_a} \right) \frac{\sigma^2}{B}.$$

672 It is left to apply Lemma 3 with

$$\begin{aligned} \Psi^t &= \frac{(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ &+ \frac{1}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{8b\omega(2\omega+1)}{np_a^2} + \frac{2(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \end{aligned}$$

673 and  $C = \left( \frac{24b^2\omega(2\omega+1)}{p_a^2} + \frac{6b}{p_a} \right) \frac{\sigma^2}{nB}$  to conclude the proof.  $\square$

674 **Corollary 3.** Suppose that assumptions from Theorem 4 hold, momentum  $b =$   
675  $\Theta \left( \min \left\{ \frac{p_a}{\omega} \sqrt{\frac{n\varepsilon B}{\sigma^2}}, \frac{p_a n \varepsilon B}{\sigma^2} \right\} \right)$ ,  $\frac{\sigma^2}{n\varepsilon B} \geq 1$ , and  $h_i^0 = \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0)$  for all  $i \in [n]$ ,  
676 and batch size  $B_{\text{init}} = \Theta \left( \frac{\sqrt{p_a B}}{b} \right)$ , then Algorithm 1 (DASHA-PP-MVR) needs

$$\begin{aligned} T &:= \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right. \right. \\ &\quad \left. \left. + \frac{\sigma}{p_a \sqrt{\varepsilon n}} \left( \frac{\mathbb{1}_{p_a} \hat{L}}{\sqrt{B}} + \frac{L_\sigma}{B} \right) \right] + \frac{\sigma^2}{\sqrt{p_a n \varepsilon B}} \right) \end{aligned}$$

677 communication rounds to get an  $\varepsilon$ -solution and the number of stochastic gradient calculations per  
678 node equals  $\mathcal{O}(B_{\text{init}} + BT)$ .

679 *Proof.* Using the result from Theorem 4, we have

$$\begin{aligned} &\mathbb{E} [\|\nabla f(\hat{x}^T)\|^2] \\ &\leq \frac{1}{T} \left[ 2\Delta_0 \left( L + \sqrt{\frac{48\omega(2\omega+1)}{np_a^2}} \left( \hat{L}^2 + \frac{(1-b)^2 L_\sigma^2}{B} \right) + \frac{12}{np_a b} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1-b)^2 L_\sigma^2}{B} \right) \right) \right. \\ &\quad \left. + \frac{2}{b} \|h^0 - \nabla f(x^0)\|^2 + \left( \frac{32b\omega(2\omega+1)}{np_a^2} + \frac{4 \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_a} \right) \left( \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \right] \\ &\quad + \left( \frac{48b^2\omega(2\omega+1)}{p_a^2} + \frac{12b}{p_a} \right) \frac{\sigma^2}{nB} \end{aligned}$$

680 We choose  $b$  to ensure  $\left( \frac{48b^2\omega(2\omega+1)}{p_a^2} + \frac{12b}{p_a} \right) \frac{\sigma^2}{nB} = \Theta(\varepsilon)$ . Note that  $\frac{1}{b} =$

681  $\Theta \left( \max \left\{ \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{n\varepsilon B}}, \frac{\sigma^2}{p_a n \varepsilon B} \right\} \right) \leq \Theta \left( \max \left\{ \frac{\omega^2}{p_a}, \frac{\sigma^2}{p_a n \varepsilon B} \right\} \right)$ , thus

$$\begin{aligned} &\mathbb{E} [\|\nabla f(\hat{x}^T)\|^2] \\ &= \mathcal{O} \left( \frac{1}{T} \left[ \Delta_0 \left( L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right) \right. \right. \\ &\quad \left. \left. + \frac{1}{b} \|h^0 - \nabla f(x^0)\|^2 + \left( \frac{b\omega^2}{np_a^2} + \frac{1}{np_a} \right) \left( \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \right] + \varepsilon \right), \end{aligned}$$

682 where  $\mathbb{1}_{p_a} = \sqrt{1 - \frac{p_{aa}}{p_a}}$ . It enough to take the following  $T$  to get  $\varepsilon$ -solution.

$$T = \mathcal{O} \left( \frac{1}{\varepsilon} \left[ \Delta_0 \left( L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right) \right. \right. \\ \left. \left. + \frac{1}{b} \|h^0 - \nabla f(x^0)\|^2 + \left( \frac{b\omega^2}{np_a^2} + \frac{1}{np_a} \right) \left( \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \right] \right).$$

683 Let us bound the norms:

$$\begin{aligned} \mathbb{E} \left[ \|h^0 - \nabla f(x^0)\|^2 \right] &= \mathbb{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0) - \nabla f(x^0) \right\|^2 \right] \\ &= \frac{1}{n^2 B_{\text{init}}^2} \sum_{i=1}^n \sum_{k=1}^{B_{\text{init}}} \mathbb{E} \left[ \|\nabla f_i(x^0; \xi_{ik}^0) - \nabla f_i(x^0)\|^2 \right] \\ &\leq \frac{\sigma^2}{n B_{\text{init}}}. \end{aligned}$$

684 Using the same reasoning, one can get  $\frac{1}{n} \sum_{i=1}^n \mathbb{E} \left[ \|h_i^0 - \nabla f_i(x^0)\|^2 \right] \leq \frac{\sigma^2}{B_{\text{init}}}$ . Combining all inequalities, we have

$$T = \mathcal{O} \left( \frac{1}{\varepsilon} \left[ \Delta_0 \left( L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right) \right. \right. \\ \left. \left. + \frac{\sigma^2}{bn B_{\text{init}}} + \frac{b\omega^2 \sigma^2}{np_a^2 B_{\text{init}}} + \frac{\sigma^2}{np_a B_{\text{init}}} \right] \right).$$

686 Using the choice of  $B_{\text{init}}$  and  $b$ , we obtain

$$\begin{aligned} T &= \mathcal{O} \left( \frac{1}{\varepsilon} \left[ \Delta_0 \left( L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right) \right. \right. \\ &\quad \left. \left. + \frac{\sigma^2}{\sqrt{p_a} n B} + \frac{b^2 \omega^2 \sigma^2}{np_a^{5/2} B} + \frac{b \sigma^2}{p_a^{3/2} n B} \right] \right) \\ &= \mathcal{O} \left( \frac{1}{\varepsilon} \left[ \Delta_0 \left( L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right) \right. \right. \\ &\quad \left. \left. + \frac{\sigma^2}{\sqrt{p_a} n B} + \frac{\varepsilon}{\sqrt{p_a}} \right] \right) \end{aligned}$$

$$= \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right] + \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} + \frac{1}{\sqrt{p_a}} \right).$$

687 Using  $\frac{\sigma^2}{n \varepsilon B} \geq 1$ , we can conclude the proof of the inequality. The number of stochastic gradients that  
 688 each node calculates equals  $B_{\text{init}} + 2BT = \mathcal{O}(B_{\text{init}} + BT)$ .  $\square$

689 **Corollary 4.** Suppose that assumptions of Corollary 3 hold, batch size  $B \leq \min \left\{ \frac{\sigma}{p_a \sqrt{\varepsilon n}}, \frac{L_\sigma^2}{\mathbb{1}_{p_a}^2 \hat{L}^2} \right\}$ ,  
 690 we take RandK compressors with  $K = \Theta \left( \frac{Bd\sqrt{\varepsilon n}}{\sigma} \right)$ . Then the communication complexity equals

$$\mathcal{O} \left( \frac{d\sigma}{\sqrt{p_a} \sqrt{n \varepsilon}} + \frac{L_\sigma \Delta_0 d}{p_a \sqrt{n \varepsilon}} \right), \quad (9)$$

691 and the expected number of stochastic gradient calculations per node equals

$$\mathcal{O} \left( \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} + \frac{L_\sigma \Delta_0 \sigma}{p_a \varepsilon^{3/2} n} \right). \quad (10)$$

692 *Proof.* The communication complexity equals

$$\mathcal{O}(d + KT) = \mathcal{O} \left( d + \frac{\Delta_0}{\varepsilon} \left[ KL + K \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + K \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right] + K \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} \right).$$

693 Due to  $B \leq \frac{L_\sigma^2}{\mathbb{1}_{p_a}^2 \hat{L}^2}$ , we have  $\mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \leq \frac{2L_\sigma}{\sqrt{B}}$  and

$$\mathcal{O}(d + KT) = \mathcal{O} \left( d + \frac{\Delta_0}{\varepsilon} \left[ KL + K \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + K \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \frac{L_\sigma}{\sqrt{B}} \right] + K \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} \right).$$

694 From Theorem 6, we have  $\omega + 1 = \frac{d}{K}$ . Since  $K = \Theta \left( \frac{Bd\sqrt{\varepsilon n}}{\sigma} \right) = \mathcal{O} \left( \frac{d}{p_a \sqrt{n}} \right)$ , the communication  
 695 complexity equals

$$\begin{aligned} \mathcal{O}(d + KT) &= \mathcal{O} \left( d + \frac{\Delta_0}{\varepsilon} \left[ \frac{d}{p_a \sqrt{n}} L + \frac{d}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{d}{p_a \sqrt{n}} L_\sigma \right] + \frac{d\sigma}{\sqrt{p_a} \sqrt{n \varepsilon}} \right) \\ &= \mathcal{O} \left( \frac{d\sigma}{\sqrt{p_a} \sqrt{n \varepsilon}} + \frac{L_\sigma \Delta_0 d}{p_a \sqrt{n \varepsilon}} \right) \end{aligned}$$

696 And the expected number of stochastic gradient calculations per node equals

$$\begin{aligned} &\mathcal{O}(B_{\text{init}} + BT) \\ &= \mathcal{O} \left( \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} + \frac{B\omega}{\sqrt{p_a}} \sqrt{\frac{\sigma^2}{n \varepsilon B}} + \frac{\Delta_0}{\varepsilon} \left[ BL + B \frac{\omega}{p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + B \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \left( \mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right] + B \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} \right) \\ &= \mathcal{O} \left( \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} + \frac{Bd}{K \sqrt{p_a}} \sqrt{\frac{\sigma^2}{n \varepsilon B}} + \frac{\Delta_0}{\varepsilon} \left[ BL + B \frac{d}{K p_a \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + B \sqrt{\frac{\sigma^2}{p_a^2 \varepsilon n^2 B}} \frac{L_\sigma}{\sqrt{B}} \right] + \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} \right) \end{aligned}$$

$$\begin{aligned}
&= \mathcal{O} \left( \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} + \frac{\sigma^2}{\sqrt{p_a} n \varepsilon \sqrt{B}} + \frac{\Delta_0}{\varepsilon} \left[ \frac{\sigma}{p_a \sqrt{\varepsilon} n} L + \frac{\sigma}{p_a \sqrt{\varepsilon} n} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a \sqrt{\varepsilon} n} L_\sigma \right] \right) \\
&= \mathcal{O} \left( \frac{\sigma^2}{\sqrt{p_a} n \varepsilon} + \frac{L_\sigma \Delta_0 \sigma}{p_a \varepsilon^{3/2} n} \right).
\end{aligned}$$

697

□

## E Analysis of DASHA-PP under Polyak-Łojasiewicz Condition

In this section, we provide the theoretical convergence rates of DASHA-PP under Polyak-Łojasiewicz Condition.

**Assumption 9.** The function  $f$  satisfy (Polyak-Łojasiewicz) PL-condition:

$$\|\nabla f(x)\|^2 \geq 2\mu(f(x) - f^*), \quad \forall x \in \mathbb{R}, \quad (28)$$

where  $f^* = \inf_{x \in \mathbb{R}^d} f(x) > -\infty$ .

Under Polyak-Łojasiewicz condition, a (random) point  $\hat{x}$  is  $\varepsilon$ -solution, if  $\mathbb{E}[f(\hat{x})] - f^* \leq \varepsilon$ .

We now provide the convergence rates of DASHA-PP under PL-condition.

### E.1 Gradient Setting

**Theorem 8.** Suppose that Assumption 1, 2, 3, 7, 8 and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_a}{2-p_a}$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{200\omega(2\omega+1)}{np_a^2} + \frac{48}{np_a^2} \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}} \right)^{-1}, \frac{a}{4\mu} \right\},$$

and  $h_i^0 = g_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP), then  $\mathbb{E}[f(x^T)] - f^* \leq (1 - \gamma\mu)^T \Delta_0$ .

Let us provide bounds up to logarithmic factors and use  $\tilde{\mathcal{O}}(\cdot)$  notation. The provided theorem states that to get  $\varepsilon$ -solution DASHA-PP have to run

$$\tilde{\mathcal{O}} \left( \frac{\omega+1}{p_a} + \frac{L}{\mu} + \frac{\omega \hat{L}}{p_a \mu \sqrt{n}} + \frac{\hat{L}}{p_a \mu \sqrt{n}} \right),$$

communication rounds. The method DASHA from (Tyurin and Richtárik, 2023), have to run

$$\tilde{\mathcal{O}} \left( \omega + \frac{L}{\mu} + \frac{\omega \hat{L}}{\mu \sqrt{n}} \right),$$

communication rounds to get  $\varepsilon$ -solution. The difference is the same as in the general nonconvex case (see Section 6.1). Up to Lipschitz constants factors, we get the degeneration up to  $1/p_a$  factor due to the partial participation.

### E.2 Finite-Sum Setting

**Theorem 9.** Suppose that Assumption 1, 2, 3, 7, 4, 8, and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ , probability  $p_{page} = \frac{B}{m+B}$ ,  $b = \frac{p_{page} p_a}{2-p_a}$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{200\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1-p_{page})L_{\max}^2}{B} \right) + \frac{48}{np_a^2 p_{page}} \left( \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 + \frac{(1-p_{page})L_{\max}^2}{B} \right)} \right)^{-1}, \frac{a}{2\mu}, \frac{b}{2\mu} \right\},$$

and  $h_i^0 = g_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-PAGE), then  $\mathbb{E}[f(x^T)] - f^* \leq (1 - \gamma\mu)^T \Delta_0$ .

The provided theorem states that to get  $\varepsilon$ -solution DASHA-PP have to run

$$\tilde{\mathcal{O}} \left( \frac{\omega+1}{p_a} + \frac{m}{p_a B} + \frac{L}{\mu} + \frac{\omega}{p_a \mu \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + \frac{\sqrt{m}}{p_a \mu \sqrt{n} B} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) \right),$$

communication rounds. The method DASHA-PAGE from (Tyurin and Richtárik, 2023), have to run

$$\tilde{\mathcal{O}} \left( \omega + \frac{m}{B} + \frac{L}{\mu} + \frac{\omega}{\mu \sqrt{n}} \left( \hat{L} + \frac{L_{\max}}{\sqrt{B}} \right) + \frac{\sqrt{m}}{\mu \sqrt{n} B} \left( \frac{L_{\max}}{\sqrt{B}} \right) \right),$$

communication rounds to get  $\varepsilon$ -solution. We can guarantee the degeneration up to  $1/p_a$  factor due to the partial participation only if  $B = \mathcal{O}\left(\frac{L_{\max}^2}{L^2}\right)$ . The same conclusion we have in Section 6.2.

### 721 E.3 Stochastic Setting

**Theorem 10.** Suppose that Assumption 1, 2, 3, 7, 5, 6, 8 and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  
 $b \in \left(0, \frac{p_a}{2-p_a}\right]$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{200\omega(2\omega+1)}{np_a^2} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \hat{L}^2 \right)} + \frac{40}{np_a b} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 \right) \right)^{-1}, \frac{a}{2\mu}, \frac{b}{2\mu} \right\},$$

722 and  $h_i^0 = g_i^0$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-MVR), then

$$\begin{aligned} & \mathbb{E} [f(x^T) - f^*] \\ & \leq (1 - \gamma\mu)^T \left( \Delta_0 + \frac{2\gamma}{b} \|h^0 - \nabla f(x^0)\|^2 + \left( \frac{40\gamma b\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \\ & \quad + \frac{1}{\mu} \left( \frac{100b^2\omega(2\omega+1)}{p_a^2} + \frac{20b}{p_a} \right) \frac{\sigma^2}{nB}. \end{aligned}$$

723 The provided theorems states that to get  $\varepsilon$ -solution DASHA-PP have to run

$$\tilde{\mathcal{O}} \left( \underbrace{\frac{\omega+1}{p_a} + \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{\mu n \varepsilon B}}}_{\mathcal{P}_2} + \frac{\sigma^2}{p_a \mu n \varepsilon B} + \frac{L}{\mu} + \frac{\omega}{p_a \mu \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \underbrace{\frac{\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon B}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right)}_{\mathcal{P}_1} \right) \quad (29)$$

724 communication rounds. We take  $b = \Theta \left( \min \left\{ \frac{p_a}{\omega} \sqrt{\frac{\mu n \varepsilon B}{\sigma^2}}, \frac{p_a \mu n \varepsilon B}{\sigma^2} \right\} \right) \geq$   
 725  $\Theta \left( \min \left\{ \frac{p_a}{\omega^2}, \frac{p_a \mu n \varepsilon B}{\sigma^2} \right\} \right).$

726 The method DASHA-SYNC-MVR from (Tyurin and Richtárik, 2023), have to run

$$\tilde{\mathcal{O}} \left( \omega + \frac{\sigma^2}{\mu n \varepsilon B} + \frac{L}{\mu} + \frac{\omega}{\mu \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{n \mu^{3/2} \sqrt{\varepsilon B}} \left( \frac{L_\sigma}{\sqrt{B}} \right) \right) \quad (30)$$

727 communication rounds to get  $\varepsilon$ -solution<sup>7</sup>.

728 In the stochastic setting, the comparison is a little bit more complicated. As in the finite-sum setting,  
 729 we have to take  $B = \mathcal{O} \left( \frac{L_\sigma^2}{\hat{L}^2} \right)$  to guarantee the degeneration up to  $1/p_a$  of the term  $\mathcal{P}_1$  from (29).

730 However, DASHA-PP-MVR has also suboptimal term  $\mathcal{P}_2$ . This suboptimality is tightly connected with  
 731 the suboptimality of  $B_{\text{init}}$  in the general nonconvex case, which we discuss in Section 6.3, and it also  
 732 appears in the analysis of DASHA-MVR (Tyurin and Richtárik, 2023). Let us provide the counterpart  
 733 of Corollary 4. The corollary reveals that we can escape regimes when  $\mathcal{P}_2$  is the bottleneck by  
 734 choosing the parameters of the compressors.

735 **Corollary 5.** Suppose that assumptions of Theorem 10 hold, batch size  $B \leq \min \left\{ \frac{\sigma}{p_a \sqrt{\mu \varepsilon n}}, \frac{L_\sigma^2}{\hat{L}^2} \right\}$ ,  
 736 we take RandK compressors with  $K = \Theta \left( \frac{B d \sqrt{\mu \varepsilon n}}{\sigma} \right)$ . Then the communication complexity equals

$$\tilde{\mathcal{O}} \left( \frac{d\sigma}{p_a \sqrt{\mu \varepsilon n}} + \frac{dL_\sigma}{p_a \mu \sqrt{n}} \right),$$

737 and the expected number of stochastic gradient calculations per node equals

$$\tilde{\mathcal{O}} \left( \frac{\sigma^2}{p_a \mu n \varepsilon} + \frac{\sigma L_\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon}} \right).$$

738 Up to Lipschitz constants, DASHA-PP-MVR has the state-of-the-art oracle complexity under PL-  
 739 condition (see (Li et al., 2021a)). Moreover, DASHA-PP-MVR has the state-of-the-art communication  
 740 complexity of DASHA for a small enough  $\mu$ .

<sup>7</sup>For simplicity, we omitted  $\frac{d}{\zeta_C}$  term from the complexity in the stochastic setting, where  $\zeta_C$  is defined in Definition 12. For instance, for the RandK compressor (see Definition 5 and Theorem 6),  $\zeta_C = K$  and  $\frac{d}{\zeta_C} = \Theta(\omega)$ .

741 **E.4 Proofs of Theorems**

742 The following proofs almost repeat the proofs from Section D. And one of the main changes is that  
743 instead of Lemma 3, we use the following lemma.

744 **E.4.1 Standard Lemma under Polyak-Łojasiewicz Condition**

745 **Lemma 11.** *Suppose that Assumptions 1 and 9 hold and*

$$\mathbb{E} [f(x^{t+1})] + \gamma \Psi^{t+1} \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] + (1 - \gamma\mu)\gamma \Psi^t + \gamma C,$$

746 *where  $\Psi^t$  is a sequence of numbers,  $\Psi^t \geq 0$  for all  $t \in [T]$ , constant  $C \geq 0$ , constant  $\mu > 0$ , and*  
747 *constant  $\gamma \in (0, 1/\mu)$ . Then*

$$\mathbb{E} [f(x^T) - f^*] \leq (1 - \gamma\mu)^T ((f(x^0) - f^*) + \gamma \Psi^0) + \frac{C}{\mu}. \quad (31)$$

748 *Proof.* We subtract  $f^*$  and use PL-condition (28) to get

$$\begin{aligned} \mathbb{E} [f(x^{t+1}) - f^*] + \gamma \Psi^{t+1} &\leq \mathbb{E} [f(x^t) - f^*] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] + \gamma \Psi^t + \gamma C \\ &\leq (1 - \gamma\mu) \mathbb{E} [f(x^t) - f^*] + (1 - \gamma\mu)\gamma \Psi^t + \gamma C \\ &= (1 - \gamma\mu) (\mathbb{E} [f(x^t) - f^*] + \gamma \Psi^t) + \gamma C. \end{aligned}$$

749 Unrolling the inequality, we have

$$\begin{aligned} \mathbb{E} [f(x^{t+1}) - f^*] + \gamma \Psi^{t+1} &\leq (1 - \gamma\mu)^{t+1} ((f(x^0) - f^*) + \gamma \Psi^0) + \gamma C \sum_{i=0}^t (1 - \gamma\mu)^i \\ &\leq (1 - \gamma\mu)^{t+1} ((f(x^0) - f^*) + \gamma \Psi^0) + \frac{C}{\mu}. \end{aligned}$$

750 It is left to note that  $\Psi^t \geq 0$  for all  $t \in [T]$ . □

751 **E.4.2 Generic Lemma**

752 We now provide the counterpart of Lemma 6.

753 **Lemma 12.** *Suppose that Assumptions 2, 7, 8 and 9 hold and let us take  $a = \frac{p_a}{2\omega+1}$ , then*

$$\begin{aligned} &\mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ &\leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ &\quad + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ &\quad + \frac{10\gamma(2\omega+1)\omega}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right]. \end{aligned}$$

754 *Proof.* Let us fix some constants  $\kappa, \eta \in [0, \infty)$  that we will define later. Using the same reasoning as  
755 in Lemma 6, we can get

$$\begin{aligned} &\mathbb{E} [f(x^{t+1})] \\ &\quad + \kappa \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ &\leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \end{aligned}$$

$$\begin{aligned}
& + \left( \gamma + \kappa (1 - a)^2 \right) \mathbb{E} \left[ \|g^t - h^t\|^2 \right] \\
& + \left( \frac{\kappa a^2 ((2\omega + 1) p_a - p_{aa})}{np_a^2} + \eta \left( \frac{a^2 (2\omega + 1 - p_a)}{p_a} + (1 - a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( \frac{2\kappa\omega}{np_a} + \frac{2\eta\omega}{p_a} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right].
\end{aligned}$$

756 Let us take  $\kappa = \frac{2\gamma}{a}$ . One can show that  $\gamma + \kappa (1 - a)^2 \leq (1 - \frac{a}{2}) \kappa$ , and thus

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] \\
& + \frac{2\gamma}{a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma}{a} \mathbb{E} [\|g^t - h^t\|^2] \\
& + \left( \frac{2\gamma a ((2\omega + 1) p_a - p_{aa})}{np_a^2} + \eta \left( \frac{a^2 (2\omega + 1 - p_a)}{p_a} + (1 - a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( \frac{4\gamma\omega}{anp_a} + \frac{2\eta\omega}{p_a} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right].
\end{aligned}$$

757 Considering the choice of  $a$ , one can show that  $\left( \frac{a^2 (2\omega + 1 - p_a)}{p_a} + (1 - a)^2 \right) \leq 1 - a$ . If we take  
758  $\eta = \frac{4\gamma((2\omega+1)p_a-p_{aa})}{np_a^2}$ , then  $\left( \frac{2\gamma a ((2\omega + 1) p_a - p_{aa})}{np_a^2} + \eta \left( \frac{a^2 (2\omega + 1 - p_a)}{p_a} + (1 - a)^2 \right) \right) \leq (1 - \frac{a}{2}) \eta$  and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] \\
& + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1) p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \left( 1 - \frac{a}{2} \right) \frac{4\gamma((2\omega + 1) p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( \frac{2\gamma(2\omega + 1)\omega}{np_a^2} + \frac{8\gamma((2\omega + 1) p_a - p_{aa})\omega}{np_a^3} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \\
& \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \left( 1 - \frac{a}{2} \right) \frac{4\gamma((2\omega + 1) p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{10\gamma(2\omega + 1)\omega}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right].
\end{aligned}$$

759 It is left to consider that  $\gamma \leq \frac{a}{2\mu}$ , and therefore  $1 - \frac{a}{2} \leq 1 - \gamma\mu$ . □



760 **E.4.3 Proof for DASHA-PP under PL-condition**

**Theorem 8.** Suppose that Assumption 1, 2, 3, 7, 8 and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_a}{2-p_a}$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{200\omega(2\omega+1)}{np_a^2} + \frac{48}{np_a^2} \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}} \right)^{-1}, \frac{a}{4\mu} \right\},$$

761 and  $h_i^0 = g_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP), then  $\mathbb{E}[f(x^T)] - f^* \leq$   
 762  $(1 - \gamma\mu)^T \Delta_0$ .

763 *Proof.* Let us fix constants  $\nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 12, Lemma 7,  
 764 and the law of total expectation, we obtain

$$\begin{aligned} & \mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\ & + \nu \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\ & \leq \mathbb{E}\left[f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left(\frac{1}{2\gamma} - \frac{L}{2}\right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2\right] \\ & + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\ & + \frac{10\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E}\left[2\widehat{L}^2 \|x^{t+1} - x^t\|^2 + 2b^2 \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\ & + \nu \mathbb{E}\left[\frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \|x^{t+1} - x^t\|^2 + \frac{2b^2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2\right] \\ & + \rho \mathbb{E}\left[\frac{2(1-p_a)\widehat{L}^2}{p_a} \|x^{t+1} - x^t\|^2 + \left(\frac{2b^2(1-p_a)}{p_a} + (1-b)^2\right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right]. \end{aligned}$$

765 After rearranging the terms, we get

$$\begin{aligned} & \mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\ & + \nu \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\ & \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\ & + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\ & - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{20\gamma\omega(2\omega+1)\widehat{L}^2}{np_a^2} - \nu \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} - \rho \frac{2(1-p_a)\widehat{L}^2}{p_a}\right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\ & + (\gamma + \nu(1-b)^2) \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] \\ & + \left(\frac{20b^2\gamma\omega(2\omega+1)}{np_a^2} + \nu \frac{2b^2(p_a - p_{aa})}{np_a^2} + \rho \left(\frac{2b^2(1-p_a)}{p_a} + (1-b)^2\right)\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right]. \end{aligned}$$

766 By taking  $\nu = \frac{2\gamma}{b}$ , one can show that  $(\gamma + \nu(1-b)^2) \leq (1 - \frac{b}{2})\nu$ , and

$$\mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right]$$

$$\begin{aligned}
& + \frac{2\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{20\gamma\omega(2\omega + 1)\hat{L}^2}{np_a^2} - \frac{4\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} - \rho \frac{2(1 - p_a)\hat{L}^2}{p_a} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left( 1 - \frac{b}{2} \right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{20b^2\gamma\omega(2\omega + 1)}{np_a^2} + \frac{4\gamma b(p_a - p_{aa})}{np_a^2} + \rho \left( \frac{2b^2(1 - p_a)}{p_a} + (1 - b)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

767 Note that  $b = \frac{p_a}{2 - p_a}$ , thus

$$\begin{aligned}
& \left( \frac{20b^2\gamma\omega(2\omega + 1)}{np_a^2} + \frac{4\gamma b(p_a - p_{aa})}{np_a^2} + \rho \left( \frac{2b^2(1 - p_a)}{p_a} + (1 - b)^2 \right) \right) \\
& \leq \left( \frac{20b^2\gamma\omega(2\omega + 1)}{np_a^2} + \frac{4\gamma b(p_a - p_{aa})}{np_a^2} + \rho(1 - b) \right).
\end{aligned}$$

768 And if we take  $\rho = \frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}$ , then

$$\left( \frac{20b^2\gamma\omega(2\omega + 1)}{np_a^2} + \frac{4\gamma b(p_a - p_{aa})}{np_a^2} + \rho(1 - b) \right) \leq \left( 1 - \frac{b}{2} \right) \rho,$$

769 and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{20\gamma\omega(2\omega + 1)\hat{L}^2}{np_a^2} - \frac{4\gamma(p_a - p_{aa})\hat{L}^2}{bnp_a^2} \right. \\
& \quad \left. - \frac{80b\gamma\omega(2\omega + 1)(1 - p_a)\hat{L}^2}{np_a^3} - \frac{16\gamma(p_a - p_{aa})(1 - p_a)\hat{L}^2}{np_a^3} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left( 1 - \frac{b}{2} \right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( 1 - \frac{b}{2} \right) \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

770 Due to  $\frac{p_a}{2} \leq b \leq p_a$ , we have

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{100\gamma\omega(2\omega + 1)\hat{L}^2}{np_a^2} - \frac{24\gamma(p_a - p_{aa})\hat{L}^2}{np_a^3}\right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
&\quad + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left(\frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
\end{aligned}$$

771 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
&\mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
&\quad + \frac{2\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left(\frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
\end{aligned}$$

772 Note that  $\gamma \leq \frac{a}{4\mu} \leq \frac{p_a}{4\mu} \leq \frac{b}{2\mu}$ , thus  $1 - \frac{b}{2} \leq 1 - \gamma\mu$  and

$$\begin{aligned}
&\mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
&\quad + \frac{2\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad + (1 - \gamma\mu) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + (1 - \gamma\mu) \left(\frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
\end{aligned}$$

773 In the view of Lemma 11 with

$$\begin{aligned}
\Psi^t &= \frac{2(2\omega + 1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{4((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad + \frac{2}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(\frac{40b\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right],
\end{aligned}$$

774 we can conclude the proof of the theorem.  $\square$

#### 775 E.4.4 Proof for DASHA-PP-PAGE under PL-condition

**Theorem 9.** Suppose that Assumption 1, 2, 3, 7, 4, 8, and 9 hold. Let us take  $a = \frac{p_a}{2\omega + 1}$ , probability

$$p_{\text{page}} = \frac{B}{m+B}, b = \frac{p_{\text{page}} p_a}{2-p_a},$$

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{200\omega(2\omega + 1)}{np_a^2} \left( \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right)} + \frac{48}{np_a^2 p_{\text{page}}} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right)^{-1}, \frac{a}{2\mu}, \frac{b}{2\mu} \right\},$$

776 and  $h_i^0 = g_i^0 = \nabla f_i(x^0)$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-PAGE), then  $\mathbb{E}[f(x^T)] - f^* \leq$   
 777  $(1 - \gamma\mu)^T \Delta_0$ .

778 *Proof.* Let us fix constants  $\nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 12, Lemma 8,  
 779 and the law of total expectation, we obtain

$$\begin{aligned}
 & \mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
 & + \nu \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
 & \leq \mathbb{E}\left[f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left(\frac{1}{2\gamma} - \frac{L}{2}\right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2\right] \\
 & + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
 & + \frac{10\gamma(2\omega+1)\omega}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2\right] \\
 & + \nu \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
 & \leq \mathbb{E}\left[f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left(\frac{1}{2\gamma} - \frac{L}{2}\right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2\right] \\
 & + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
 & + \frac{10\gamma(2\omega+1)\omega}{np_a^2} \mathbb{E}\left[\left(2\hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B}\right) \|x^{t+1} - x^t\|^2 + \frac{2b^2}{p_{\text{page}}} \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\
 & + \nu \mathbb{E}\left[\left(\frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} + \frac{(1 - p_{\text{page}})L_{\max}^2}{np_a B}\right) \|x^{t+1} - x^t\|^2\right. \\
 & \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{page}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left(p_{\text{page}} \left(1 - \frac{b}{p_{\text{page}}}\right)^2 + (1 - p_{\text{page}})\right) \|h^t - \nabla f(x^t)\|^2\right] \\
 & + \rho \mathbb{E}\left[\left(\frac{2(1 - p_a)\hat{L}^2}{p_a} + \frac{(1 - p_{\text{page}})L_{\max}^2}{p_a B}\right) \|x^{t+1} - x^t\|^2\right. \\
 & \quad \left. + \left(\frac{2(1 - p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left(1 - \frac{b}{p_{\text{page}}}\right)^2 + (1 - p_{\text{page}})\right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right].
 \end{aligned}$$

780 After rearranging the terms, we get

$$\begin{aligned}
 & \mathbb{E}[f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
 & + \nu \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
 & \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
 & + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right]
 \end{aligned}$$

$$\begin{aligned}
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{10\gamma\omega(2\omega+1)}{np_a^2} \left( 2\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \nu \left( \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} + \frac{(1-p_{\text{page}})L_{\max}^2}{np_a B} \right) - \rho \left( \frac{2(1-p_a)\hat{L}^2}{p_a} + \frac{(1-p_{\text{page}})L_{\max}^2}{p_a B} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left( \gamma + \nu \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{2\nu(p_a - p_{aa})b^2}{np_a^2 p_{\text{page}}} \right. \\
& \quad \left. + \rho \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

Due to  $b = \frac{p_{\text{page}} p_a}{2-p_a} \leq p_{\text{page}}$ , one can show that  $\left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \leq 1-b$ . Thus, if we take  $\nu = \frac{2\gamma}{b}$ , then

$$\left( \gamma + \nu \left( p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \leq \gamma + \nu(1-b) = \left( 1 - \frac{b}{2} \right) \nu,$$

781 therefore

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{10\gamma\omega(2\omega+1)}{np_a^2} \left( 2\hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \frac{2\gamma}{bn p_a} \left( 2 \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1-p_{\text{page}})L_{\max}^2}{B} \right) - \rho \left( \frac{2(1-p_a)\hat{L}^2}{p_a} + \frac{(1-p_{\text{page}})L_{\max}^2}{p_a B} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left( 1 - \frac{b}{2} \right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{4\gamma(p_a - p_{aa})b}{np_a^2 p_{\text{page}}} \right. \\
& \quad \left. + \rho \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

Next, with the choice of  $b = \frac{p_{\text{page}} p_a}{2-p_a}$ , we ensure that

$$\left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \leq 1-b.$$

If we take  $\rho = \frac{40b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}}$ , then

$$\left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{4\gamma(p_a - p_{aa})b}{np_a^2 p_{\text{page}}} + \rho \left( \frac{2(1-p_a)b^2}{p_a p_{\text{page}}} + p_{\text{page}} \left( 1 - \frac{b}{p_{\text{page}}} \right)^2 + (1-p_{\text{page}}) \right) \right) \leq \left( 1 - \frac{b}{2} \right) \rho,$$

782 therefore

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1 - \gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{10\gamma\omega(2\omega+1)}{np_a^2} \left( 2\hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \frac{2\gamma}{bnp_a} \left( 2 \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^3 p_{\text{page}}} + \frac{8\gamma \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_a^2 p_{\text{page}}} \right) \left( 2(1 - p_a) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right] \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left( 1 - \frac{b}{2} \right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( 1 - \frac{b}{2} \right) \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

Let us simplify the inequality. First, due to  $b \geq \frac{p_{\text{page}} p_a}{2}$ , we have

$$\frac{2\gamma}{bnp_a} \left( 2 \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \leq \frac{8\gamma}{np_a^2 p_{\text{page}}} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right).$$

783 Second, due to  $b \leq p_a p_{\text{page}}$  and  $p_{aa} \leq p_a^2$ , we get

$$\begin{aligned}
& \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^3 p_{\text{page}}} + \frac{8\gamma \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_a^2 p_{\text{page}}} \right) \left( 2(1 - p_a) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \\
& \leq \left( \frac{40\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_a^2 p_{\text{page}}} \right) \left( 2 \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \\
& \leq \frac{80\gamma\omega(2\omega+1)}{np_a^2} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \\
& \quad + \frac{16\gamma \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_a^2 p_{\text{page}}} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \\
& \leq \frac{80\gamma\omega(2\omega+1)}{np_a^2} \left( \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \\
& \quad + \frac{16\gamma}{np_a^2 p_{\text{page}}} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right).
\end{aligned}$$

784 Combining all bounds together, we obtain the following inequality:

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2]
\end{aligned}$$

$$\begin{aligned}
& + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{100\gamma\omega(2\omega + 1)}{np_a^2} \left( \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right. \\
& \quad \left. - \frac{24\gamma}{np_a^2 p_{\text{page}}} \left( \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 + \frac{(1 - p_{\text{page}})L_{\max}^2}{B} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

785 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

786 Note that  $\gamma \leq \frac{b}{2\mu}$ , thus  $1 - \frac{b}{2} \leq 1 - \gamma\mu$  and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{4\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + (1 - \gamma\mu) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + (1 - \gamma\mu) \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2 p_{\text{page}}} + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right].
\end{aligned}$$

787 It is left to apply Lemma 11 with

$$\begin{aligned}
\Psi^t & = \frac{2(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{4((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{2}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left( \frac{40b\omega(2\omega + 1)}{np_a^2 p_{\text{page}}} + \frac{8(p_a - p_{aa})}{np_a^2 p_{\text{page}}} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right]
\end{aligned}$$

788 to conclude the proof.  $\square$

789 **E.4.5 Proof for DASHA-PP-MVR under PL-condition**

**Theorem 10.** Suppose that Assumption 1, 2, 3, 7, 5, 6, 8 and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  
 $b \in \left(0, \frac{p_a}{2-p_a}\right]$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{200\omega(2\omega+1)}{np_a^2} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \widehat{L}^2 \right) + \frac{40}{np_a b} \left( \frac{(1-b)^2 L_\sigma^2}{B} + \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2 \right)} \right)^{-1}, \frac{a}{2\mu}, \frac{b}{2\mu} \right\},$$

790 and  $h_i^0 = g_i^0$  for all  $i \in [n]$  in Algorithm 1 (DASHA-PP-MVR), then

$$\begin{aligned} & \mathbb{E} [f(x^T) - f^*] \\ & \leq (1-\gamma\mu)^T \left( \Delta_0 + \frac{2\gamma}{b} \|h^0 - \nabla f(x^0)\|^2 + \left( \frac{40\gamma b\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \\ & \quad + \frac{1}{\mu} \left( \frac{100b^2\omega(2\omega+1)}{p_a^2} + \frac{20b}{p_a} \right) \frac{\sigma^2}{nB}. \end{aligned}$$

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & \quad + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & \quad + \frac{10\gamma(2\omega+1)\omega}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right]. \end{aligned}$$

791 *Proof.* Let us fix constants  $\nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 12, Lemma 10,  
 792 and the law of total expectation, we obtain

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & \quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & \quad + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & \quad + \frac{10\gamma(2\omega+1)\omega}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|k_i^{t+1}\|^2 \right] \\ & \quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \|h^t - \nabla f(x^t)\|^2 \right] \\ & \quad + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \end{aligned}$$



$$\begin{aligned}
& + \frac{10\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[ \frac{2b^2\sigma^2}{B} + \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \|x^{t+1} - x^t\|^2 + 2b^2 \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \nu \mathbb{E} \left( \frac{2b^2\sigma^2}{np_a B} + \left( \frac{2(1-b)^2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b)^2 \|h^t - \nabla f(x^t)\|^2 \right) \\
& + \rho \mathbb{E} \left( \frac{2b^2\sigma^2}{p_a B} + \left( \frac{2(1-b)^2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \right. \\
& \quad \left. + \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right).
\end{aligned}$$

793 After rearranging the terms, we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{10\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \right. \\
& \quad \left. - \nu \left( \frac{2(1-b)^2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2(1-b)^2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + (\gamma + \nu(1-b)^2) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{2\nu(p_a - p_{aa})b^2}{np_a^2} + \rho \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2} + \nu \frac{2b^2}{np_a} + \rho \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

794 By taking  $\nu = \frac{2\gamma}{b}$ , one can show that  $(\gamma + \nu(1-b)^2) \leq (1 - \frac{b}{2})\nu$ , and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{10\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \right.
\end{aligned}$$

$$\begin{aligned}
& -\frac{2\gamma}{b} \left( \frac{2(1-b)^2 L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa}) \hat{L}^2}{np_a^2} \right) - \rho \left( \frac{2(1-b)^2 L_\sigma^2}{p_a B} + \frac{2(1-p_a) \hat{L}^2}{p_a} \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
& + \left( \frac{20b^2 \gamma \omega (2\omega + 1)}{np_a^2} + \frac{4\gamma (p_a - p_{aa}) b}{np_a^2} + \rho \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{20b^2 \gamma \omega (2\omega + 1)}{np_a^2} + \frac{4\gamma b}{np_a} + \rho \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

795 Note that  $b \leq \frac{p_a}{2-p_a}$ , thus

$$\begin{aligned}
& \left( \frac{20b^2 \gamma \omega (2\omega + 1)}{np_a^2} + \frac{4\gamma (p_a - p_{aa}) b}{np_a^2} + \rho \left( \frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \right) \\
& \leq \left( \frac{20b^2 \gamma \omega (2\omega + 1)}{np_a^2} + \frac{4\gamma (p_a - p_{aa}) b}{np_a^2} + \rho (1-b) \right).
\end{aligned}$$

796 And if we take  $\rho = \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a-p_{aa})}{np_a^2}$ , then

$$\left( \frac{20b^2 \gamma \omega (2\omega + 1)}{np_a^2} + \frac{4\gamma (p_a - p_{aa}) b}{np_a^2} + \rho (1-b) \right) \leq \rho,$$

797 and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a-p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{10\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2 L_\sigma^2}{B} + 2\hat{L}^2 \right) \right. \\
& \quad \left. - \frac{2\gamma}{np_a b} \left( \frac{2(1-b)^2 L_\sigma^2}{B} + 2 \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^3} + \frac{8\gamma \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2} \right) \left( \frac{2(1-b)^2 L_\sigma^2}{B} + 2(1-p_a) \hat{L}^2 \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a-p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{20b^2 \gamma \omega (2\omega + 1)}{np_a^2} + \frac{4\gamma b}{np_a} + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a-p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

798 Let us simplify the inequality. First, due to  $b \leq p_a$  and  $(1-p_a) \leq \left(1 - \frac{p_{aa}}{p_a}\right)$ , we have

$$\left( \frac{40b\gamma\omega(2\omega+1)}{np_a^3} + \frac{2\gamma \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2} \right) \left( \frac{2(1-b)^2 L_\sigma^2}{B} + 8(1-p_a) \hat{L}^2 \right)$$

$$\begin{aligned}
&= \frac{40b\gamma\omega(2\omega+1)}{np_a^3} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2(1-p_a)\widehat{L}^2 \right) \\
&\quad + \frac{8\gamma \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2(1-p_a)\widehat{L}^2 \right) \\
&\leq \frac{40\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \\
&\quad + \frac{8\gamma}{np_ab} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2 \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2 \right),
\end{aligned}$$

799 therefore

$$\begin{aligned}
&\mathbb{E}[f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\
&\quad + \frac{2\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{50\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2\widehat{L}^2 \right) \right. \\
&\quad \left. - \frac{10\gamma}{np_ab} \left( \frac{2(1-b)^2L_\sigma^2}{B} + 2 \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2 \right) \right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
&\quad + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\
&\quad + \left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{4\gamma b}{np_a} + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B} \\
&\leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
&\quad + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{100\gamma\omega(2\omega+1)}{np_a^2} \left( \frac{(1-b)^2L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
&\quad \left. - \frac{20\gamma}{np_ab} \left( \frac{(1-b)^2L_\sigma^2}{B} + \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2 \right) \right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
&\quad + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\
&\quad + \left( \frac{20b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{4\gamma b}{np_a} + \left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

800 Also, we can simplify the last term:

$$\begin{aligned}
&\left( \frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \\
&= \frac{80b^3\gamma\omega(2\omega+1)}{np_a^3} + \frac{16b^2\gamma \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a^2}
\end{aligned}$$

$$\leq \frac{80b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{16b\gamma}{np_a},$$

801 thus

$$\begin{aligned} & \mathbb{E}[f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\ & + \frac{2\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\ & \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\ & + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\ & - \left(\frac{1}{2\gamma} - \frac{L}{2} - \frac{100\gamma\omega(2\omega+1)}{np_a^2} \left(\frac{(1-b)^2 L_\sigma^2}{B} + \widehat{L}^2\right)\right. \\ & \quad \left. - \frac{20\gamma}{np_a b} \left(\frac{(1-b)^2 L_\sigma^2}{B} + \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2\right)\right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\ & + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left(\frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\ & + \left(\frac{100b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{20\gamma b}{np_a}\right) \frac{\sigma^2}{B}. \end{aligned}$$

802 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned} & \mathbb{E}[f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\ & + \frac{2\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\ & \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\ & + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \\ & + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \left(\frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2\right] \\ & + \left(\frac{100b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{20\gamma b}{np_a}\right) \frac{\sigma^2}{B}. \end{aligned}$$

803 Note that  $\gamma \leq \frac{b}{2\mu}$ , thus  $1 - \frac{b}{2} \leq 1 - \gamma\mu$  and

$$\begin{aligned} & \mathbb{E}[f(x^{t+1})] + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2\right] \\ & + \frac{2\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \left(\frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2}\right) \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2\right] \\ & \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\ & + (1-\gamma\mu) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + (1-\gamma\mu) \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E}\left[\frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2\right] \end{aligned}$$

$$\begin{aligned}
& + (1 - \gamma\mu) \frac{2\gamma}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] + (1 - \gamma\mu) \left( \frac{40b\gamma\omega(2\omega + 1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{100b^2\gamma\omega(2\omega + 1)}{np_a^2} + \frac{20\gamma b}{np_a} \right) \frac{\sigma^2}{B}.
\end{aligned}$$

804 It is left to apply Lemma 11 with

$$\begin{aligned}
\Psi^t &= \frac{2(2\omega + 1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{4((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&+ \frac{2}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] + \left( \frac{40b\omega(2\omega + 1)}{np_a^2} + \frac{8(p_a - p_{aa})}{np_a^2} \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right]
\end{aligned}$$

805 and  $C = \left( \frac{100b^2\omega(2\omega+1)}{p_a^2} + \frac{20b}{p_a} \right) \frac{\sigma^2}{nB}$  to conclude the proof.  $\square$

806 **Corollary 5.** Suppose that assumptions of Theorem 10 hold, batch size  $B \leq \min \left\{ \frac{\sigma}{p_a\sqrt{\mu\varepsilon n}}, \frac{L_\sigma^2}{L^2} \right\}$ ,  
807 we take RandK compressors with  $K = \Theta \left( \frac{Bd\sqrt{\mu\varepsilon n}}{\sigma} \right)$ . Then the communication complexity equals

$$\tilde{\mathcal{O}} \left( \frac{d\sigma}{p_a\sqrt{\mu\varepsilon n}} + \frac{dL_\sigma}{p_a\mu\sqrt{n}} \right),$$

808 and the expected number of stochastic gradient calculations per node equals

$$\tilde{\mathcal{O}} \left( \frac{\sigma^2}{p_a\mu n\varepsilon} + \frac{\sigma L_\sigma}{p_a n\mu^{3/2}\sqrt{\varepsilon}} \right).$$

809 *Proof.* In the view of Theorem 10, DASHA-PP have to run

$$\tilde{\mathcal{O}} \left( \frac{\omega + 1}{p_a} + \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{\mu n\varepsilon B}} + \frac{\sigma^2}{p_a\mu n\varepsilon B} + \frac{L}{\mu} + \frac{\omega}{p_a\mu\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a n\mu^{3/2}\sqrt{\varepsilon B}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right)$$

810 communication rounds in the stochastic settings to get  $\varepsilon$ -solution. Note that  $K = \mathcal{O} \left( \frac{d}{p_a\sqrt{n}} \right)$ .

811 Moreover, we can skip the initialization procedure and initialize  $h_i^0$  and  $g_i^0$ , for instance, with zeros  
812 because the initialization error is under a logarithm. Considering Theorem 6, the communication  
813 complexity equals

$$\begin{aligned}
& \tilde{\mathcal{O}} \left( K \frac{\omega + 1}{p_a} + K \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{\mu n\varepsilon B}} + K \frac{\sigma^2}{p_a\mu n\varepsilon B} + K \frac{L}{\mu} + K \frac{\omega}{p_a\mu\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + K \frac{\sigma}{p_a n\mu^{3/2}\sqrt{\varepsilon B}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right) \\
&= \tilde{\mathcal{O}} \left( K \frac{\omega + 1}{p_a} + K \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{\mu n\varepsilon B}} + K \frac{\sigma^2}{p_a\mu n\varepsilon B} + K \frac{L}{\mu} + K \frac{\omega}{p_a\mu\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + K \frac{\sigma L_\sigma}{p_a n\mu^{3/2}\sqrt{\varepsilon B}} \right) \\
&= \tilde{\mathcal{O}} \left( \frac{d}{p_a} + \frac{d}{p_a} \sqrt{\frac{\sigma^2}{\mu n\varepsilon B}} + \frac{K\sigma^2}{p_a\mu n\varepsilon B} + \frac{dL}{p_a\mu\sqrt{n}} + \frac{d}{p_a\mu\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{K\sigma L_\sigma}{p_a n\mu^{3/2}\sqrt{\varepsilon B}} \right) \\
&= \tilde{\mathcal{O}} \left( \frac{d}{p_a} + \frac{d\sigma}{p_a\sqrt{\mu n\varepsilon B}} + \frac{d\sigma}{p_a\sqrt{\mu\varepsilon n}} + \frac{dL}{p_a\mu\sqrt{n}} + \frac{d}{p_a\mu\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{dL_\sigma}{p_a\mu\sqrt{n}} \right) \\
&= \tilde{\mathcal{O}} \left( \frac{d\sigma}{p_a\sqrt{\mu\varepsilon n}} + \frac{dL_\sigma}{p_a\mu\sqrt{n}} \right).
\end{aligned}$$

814 The expected number of stochastic gradient calculations per node equals

$$\tilde{\mathcal{O}} \left( B \frac{\omega + 1}{p_a} + B \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{\mu n\varepsilon B}} + B \frac{\sigma^2}{p_a\mu n\varepsilon B} + B \frac{L}{\mu} + B \frac{\omega}{p_a\mu\sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + B \frac{\sigma}{p_a n\mu^{3/2}\sqrt{\varepsilon B}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right)$$

$$\begin{aligned}
&= \tilde{\mathcal{O}} \left( B \frac{\omega + 1}{p_a} + B \frac{\omega}{p_a} \sqrt{\frac{\sigma^2}{\mu n \varepsilon B}} + B \frac{\sigma^2}{p_a \mu n \varepsilon B} + B \frac{L}{\mu} + B \frac{\omega}{p_a \mu \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + B \frac{\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon B}} \left( \frac{L_\sigma}{\sqrt{B}} \right) \right) \\
&= \tilde{\mathcal{O}} \left( \frac{Bd}{K p_a} + \frac{Bd}{K p_a} \sqrt{\frac{\sigma^2}{\mu n \varepsilon B}} + \frac{\sigma^2}{p_a \mu n \varepsilon} + B \frac{L}{\mu} + \frac{Bd}{K p_a \mu \sqrt{n}} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma L_\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon}} \right) \\
&= \tilde{\mathcal{O}} \left( \frac{\sigma}{p_a \sqrt{\mu \varepsilon n}} + \frac{\sigma^2}{p_a \mu \varepsilon n \sqrt{B}} + \frac{\sigma^2}{p_a \mu n \varepsilon} + \frac{\sigma L}{p_a \mu^{3/2} \sqrt{\varepsilon} n} + \frac{\sigma}{p_a \mu^{3/2} \sqrt{\varepsilon} n} \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma L_\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon}} \right) \\
&= \tilde{\mathcal{O}} \left( \frac{\sigma^2}{p_a \mu n \varepsilon} + \frac{\sigma L_\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon}} \right).
\end{aligned}$$

815

□

## 816 F Description of DASHA-PP-SYNC-MVR

817 By analogy to (Tyurin and Richtárik, 2023), we provide a “synchronized” version of the algorithm.  
 818 With a small probability, participating nodes calculate and send a mega batch without compression.  
 819 This helps us to resolve the suboptimality of DASHA-PP-MVR w.r.t.  $\omega$ . Note that this suboptimality is  
 820 not a problem. We show in Corollary 4 that DASHA-PP-MVR can have the optimal oracle complexity  
 821 and SOTA communication complexity with the particular choices of parameters of the compressors.

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### Algorithm 8 DASHA-PP-SYNC-MVR

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1: Input: starting point  $x^0 \in \mathbb{R}^d$ , stepsize  $\gamma > 0$ , momentum  $a \in (0, 1]$ , momentum  $b \in$ 
   (0, 1], probability  $p_{\text{mega}} \in (0, 1]$ , batch size  $B'$  and  $B$ , probability  $p_a \in (0, 1]$  that a node is
   participating(a), number of iterations  $T \geq 1$ .
2: Initialize  $g_i^0, h_i^0$  on the nodes and  $g^0 = \frac{1}{n} \sum_{i=1}^n g_i^0$  on the server
3: for  $t = 0, 1, \dots, T - 1$  do
4:    $x^{t+1} = x^t - \gamma g^t$ 
5:    $c^{t+1} = \begin{cases} 1, & \text{with probability } p_{\text{mega}}, \\ 0, & \text{with probability } 1 - p_{\text{mega}} \end{cases}$ 
6:   Broadcast  $x^{t+1}, x^t$  to all participating(a) nodes
7:   for  $i = 1, \dots, n$  in parallel do
8:     if  $i^{\text{th}}$  node is participating(a) then
9:       if  $c^{t+1} = 1$  then
10:        Generate i.i.d. samples  $\{\xi_{ik}^{t+1}\}_{k=1}^{B'}$  of size  $B'$  from  $\mathcal{D}_i$ .
11:         $k_i^{t+1} = \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) - \frac{b}{p_{\text{mega}}} \left( h_i^t - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) \right)$ 
12:         $m_i^{t+1} = \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t)$ 
13:       else
14:        Generate i.i.d. samples  $\{\xi_{ij}^{t+1}\}_{j=1}^B$  of size  $B$  from  $\mathcal{D}_i$ .
15:         $k_i^{t+1} = \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1})$ 
16:         $m_i^{t+1} = C_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right)$ 
17:       end if
18:        $h_i^{t+1} = h_i^t + \frac{1}{p_a} k_i^{t+1}$ 
19:        $g_i^{t+1} = g_i^t + m_i^{t+1}$ 
20:       Send  $m_i^{t+1}$  to the server
21:     else
22:        $h_i^{t+1} = h_i^t$ 
23:        $m_i^{t+1} = 0$ 
24:        $g_i^{t+1} = g_i^t$ 
25:     end if
26:   end for
27:    $g^{t+1} = g^t + \frac{1}{n} \sum_{i=1}^n m_i^{t+1}$ 
28: end for
29: Output:  $\hat{x}^T$  chosen uniformly at random from  $\{x^t\}_{k=0}^{T-1}$ 
(a): For the formal description see Section 2.2.

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822 In the following theorem, we provide the convergence rate of DASHA-PP-SYNC-MVR.

**Theorem 11.** Suppose that Assumptions 1, 2, 3, 5, 6, 7 and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  
 $b = \frac{p_{\text{mega}} p_a}{2-p_a}$ , probability  $p_{\text{mega}} \in (0, 1]$ , batch size  $B' \geq B \geq 1$

$$\gamma \leq \left( L + \sqrt{\frac{8(2\omega+1)\omega}{np_a^2} \left( \hat{L}^2 + \frac{L_\sigma^2}{B} \right) + \frac{16}{np_{\text{mega}} p_a^2} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{L_\sigma^2}{B} \right)} \right)^{-1},$$

823 and  $h_i^0 = g_i^0$  for all  $i \in [n]$  in Algorithm 8. Then

$$\begin{aligned} \mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] &\leq \frac{1}{T} \left[ \frac{2\Delta_0}{\gamma} + \frac{4}{p_{\text{mega}} p_a} \|h^0 - \nabla f(x^0)\|^2 + \frac{4 \left(1 - \frac{p_{aa}}{p_a}\right)}{n p_{\text{mega}} p_a} \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right] \\ &\quad + \frac{12\sigma^2}{nB'}. \end{aligned}$$

824 First, we introduce the expected density of compressors (Gorbunov et al., 2021; Tyurin and Richtárik, 2023).

826 **Definition 12.** The expected density of the compressor  $\mathcal{C}_i$  is  $\zeta_{\mathcal{C}_i} := \sup_{x \in \mathbb{R}^d} \mathbb{E} [\|\mathcal{C}_i(x)\|_0]$ , where  
827  $\|x\|_0$  is the number of nonzero components of  $x \in \mathbb{R}^d$ . Let  $\zeta_{\mathcal{C}} = \max_{i \in [n]} \zeta_{\mathcal{C}_i}$ .

828 Note that  $\zeta_{\mathcal{C}}$  is finite and  $\zeta_{\mathcal{C}} \leq d$ .

829 In the next corollary, we choose particular algorithm parameters to reveal the communication and  
830 oracle complexity.

**Corollary 6.** Suppose that assumptions from Theorem 11 hold, probability  $p_{\text{mega}} = \min \left\{ \frac{\zeta_{\mathcal{C}}}{d}, \frac{n\varepsilon B}{\sigma^2} \right\}$ ,  
batch size  $B' = \Theta \left( \frac{\sigma^2}{n\varepsilon} \right)$ , and  $h_i^0 = g_i^0 = \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0)$  for all  $i \in [n]$ , initial batch size  
 $B_{\text{init}} = \Theta \left( \frac{B}{p_{\text{mega}} \sqrt{p_a}} \right) = \Theta \left( \max \left\{ \frac{Bd}{\sqrt{p_a} \zeta_{\mathcal{C}}}, \frac{\sigma^2}{\sqrt{p_a} n\varepsilon} \right\} \right)$ , then DASHA-PP-SYNC-MVR needs

$$T := \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \left( \frac{\omega}{p_a \sqrt{n}} + \sqrt{\frac{d}{p_a^2 \zeta_{\mathcal{C}} n}} \right) \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a \sqrt{\varepsilon} n} \left( \frac{\hat{L}}{\sqrt{B}} + \frac{L_\sigma}{B} \right) \right] + \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} \right).$$

831 communication rounds to get an  $\varepsilon$ -solution, the expected communication complexity is equal to  
832  $\mathcal{O}(d + \zeta_{\mathcal{C}} T)$ , and the expected number of stochastic gradient calculations per node equals  $\mathcal{O}(B_{\text{init}} +$   
833  $BT)$ , where  $\zeta_{\mathcal{C}}$  is the expected density from Definition 12.

834 The main improvement of Corollary 6 over Corollary 3 is the size of the initial batch size  $B_{\text{init}}$ .  
835 However, Corollary 4 reveals that we can avoid regimes when DASHA-PP-MVR is suboptimal.

836 We also provide a theorem under PL-condition (see Assumption 9).

**Theorem 13.** Suppose that Assumptions 1, 2, 3, 5, 6, 7, 8 and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  
 $b = \frac{p_{\text{mega}} p_a}{2-p_a}$ , probability  $p_{\text{mega}} \in (0, 1]$ , batch size  $B' \geq B \geq 1$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{16(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \hat{L}^2 \right) + \left( \frac{48L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{24 \left(1 - \frac{p_{aa}}{p_a}\right) \hat{L}^2}{np_{\text{mega}} p_a^2} \right)} \right)^{-1}, \frac{a}{2\mu}, \frac{b}{2\mu} \right\},$$

837 and  $h_i^0 = g_i^0$  for all  $i \in [n]$  in Algorithm 8. Then

$$\begin{aligned} &\mathbb{E} [f(x^T) - f^*] \\ &\leq (1 - \gamma\mu)^T \left( \Delta_0 + \frac{2\gamma}{b} \|h^0 - \nabla f(x^0)\|^2 + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) + \frac{20\sigma^2}{\mu n B'}. \end{aligned}$$

838 Let us provide bounds up to logarithmic factors and use  $\tilde{\mathcal{O}}(\cdot)$  notation.

**Corollary 7.** Suppose that assumptions from Theorem 13 hold, probability  $p_{\text{mega}} =$   
 $\min \left\{ \frac{\zeta_{\mathcal{C}}}{d}, \frac{\mu n \varepsilon B}{\sigma^2} \right\}$ , batch size  $B' = \Theta \left( \frac{\sigma^2}{\mu n \varepsilon} \right)$  then DASHA-PP-SYNC-MVR needs

$$T := \tilde{\mathcal{O}} \left( \frac{\omega+1}{p_a} + \frac{d}{p_a \zeta_{\mathcal{C}}} + \frac{\sigma^2}{p_a \mu n \varepsilon B} + \frac{L}{\mu} + \frac{\omega}{p_a \mu \sqrt{n}} \left( \frac{L_\sigma}{\sqrt{B}} + \hat{L} \right) + \left( \frac{\sqrt{d}}{p_a \mu \sqrt{\zeta_{\mathcal{C}} n}} + \frac{\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon B}} \right) \left( \frac{L_\sigma}{\sqrt{B}} + \hat{L} \right) \right).$$



communication rounds to get an  $\varepsilon$ -solution, the expected communication complexity is equal to  $\tilde{\mathcal{O}}(\zeta_c T)$ , and the expected number of stochastic gradient calculations per node equals  $\tilde{\mathcal{O}}(BT)$ , where  $\zeta_c$  is the expected density from Definition 12.

The proof of this corollary almost repeats the proof of Corollary 6. Note that we can skip the initialization procedure and initialize  $h_i^0$  and  $g_i^0$ , for instance, with zeros because the initialization error is under a logarithm.

Let us assume that  $\frac{d}{\zeta_c} = \Theta(\omega)$  (holds for the RandK compressor), then the convergence rate of DASHA-PP-SYNC-MVR is

$$\tilde{\mathcal{O}}\left(\frac{\omega+1}{p_a} + \frac{\sigma^2}{p_a \mu n \varepsilon B} + \frac{L}{\mu} + \frac{\omega}{p_a \mu \sqrt{n}} \left(\frac{L_\sigma}{\sqrt{B}} + \hat{L}\right) + \frac{\sigma}{p_a n \mu^{3/2} \sqrt{\varepsilon B}} \left(\frac{L_\sigma}{\sqrt{B}} + \hat{L}\right)\right). \quad (32)$$

Comparing (32) with the rate of DASHA-PP-MVR (29), one can see that DASHA-PP-SYNC-MVR improves the suboptimal term  $\mathcal{P}_2$  from (29). However, Corollary 5 reveals that we can escape these suboptimal regimes by choosing the parameter  $K$  of RandK compressors in a particular way.

## E.1 Proof for DASHA-PP-SYNC-MVR

In this section, we provide the proof of the convergence rate for DASHA-PP-SYNC-MVR. There are four different sources of randomness in Algorithm 8: the first one from random samples  $\xi_i^{t+1}$ , the second one from compressors  $\{\mathcal{C}_i\}_{i=1}^n$ , the third one from availability of nodes, and the fourth one from  $c^{t+1}$ . We define  $\mathbb{E}_k[\cdot]$ ,  $\mathbb{E}_c[\cdot]$ ,  $\mathbb{E}_{p_a}[\cdot]$  and  $\mathbb{E}_{p_{\text{mega}}}[\cdot]$  to be conditional expectations w.r.t.  $\xi_i^{t+1}$ ,  $\{\mathcal{C}_i\}_{i=1}^n$ , availability, and  $c^{t+1}$ , accordingly, conditioned on all previous randomness. Moreover, we define  $\mathbb{E}_{t+1}[\cdot]$  to be a conditional expectation w.r.t. all randomness in iteration  $t+1$  conditioned on all previous randomness.

Let us denote

$$\begin{aligned} k_{i,1}^{t+1} &:= \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) - \frac{b}{p_{\text{mega}}} \left( h_i^t - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) \right), \\ k_{i,2}^{t+1} &:= \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}), \\ h_{i,1}^{t+1} &:= \begin{cases} h_i^t + \frac{1}{p_a} k_{i,1}^{t+1}, & i^{\text{th}} \text{ node is participating,} \\ h_i^t, & \text{otherwise,} \end{cases} \\ h_{i,2}^{t+1} &:= \begin{cases} h_i^t + \frac{1}{p_a} k_{i,2}^{t+1}, & i^{\text{th}} \text{ node is participating,} \\ h_i^t, & \text{otherwise,} \end{cases} \\ g_{i,1}^{t+1} &:= \begin{cases} g_i^t + \frac{1}{p_a} k_{i,1}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t), & i^{\text{th}} \text{ node is participating,} \\ g_i^t, & \text{otherwise,} \end{cases} \\ g_{i,2}^{t+1} &:= \begin{cases} g_i^t + \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right), & i^{\text{th}} \text{ node is participating,} \\ g_i^t, & \text{otherwise,} \end{cases} \end{aligned}$$

$h_1^{t+1} := \frac{1}{n} \sum_{i=1}^n h_{i,1}^{t+1}$ ,  $h_2^{t+1} := \frac{1}{n} \sum_{i=1}^n h_{i,2}^{t+1}$ ,  $g_1^{t+1} := \frac{1}{n} \sum_{i=1}^n g_{i,1}^{t+1}$ , and  $g_2^{t+1} := \frac{1}{n} \sum_{i=1}^n g_{i,2}^{t+1}$ . Note, that

$$h^{t+1} = \begin{cases} h_1^{t+1}, & c^{t+1} = 1, \\ h_2^{t+1}, & c^{t+1} = 0, \end{cases}$$

and

$$g^{t+1} = \begin{cases} g_1^{t+1}, & c^{t+1} = 1, \\ g_2^{t+1}, & c^{t+1} = 0 \end{cases}$$

First, we will prove two lemmas.

863 **Lemma 13.** Suppose that Assumptions 3, 5, 7 and 8 hold and let us consider sequences  $\{g_i^{t+1}\}_{i=1}^n$   
 864 and  $\{h_i^{t+1}\}_{i=1}^n$  from Algorithm 8, then

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \right] \\ & \leq \frac{2(1-p_{\text{mega}})\omega}{n^2 p_a} \sum_{i=1}^n \|k_{i,2}^{t+1}\|^2 + \left( \frac{(p_a - p_{aa})a^2}{n^2 p_a^2} + \frac{2(1-p_{\text{mega}})a^2\omega}{n^2 p_a} \right) \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \\ & \quad + (1-a)^2 \|g^t - h^t\|^2, \end{aligned}$$

865 and

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \right] \right] \\ & \leq \frac{2(1-p_{\text{mega}})\omega}{p_a} \|k_{i,2}^{t+1}\|^2 + \left( \frac{(1-p_a)a^2}{p_a} + \frac{2(1-p_{\text{mega}})a^2\omega}{p_a} \right) \|g_i^t - h_i^t\|^2 \\ & \quad + (1-a)^2 \|g_i^t - h_i^t\|^2, \quad \forall i \in [n]. \end{aligned}$$

866 *Proof.* First, we get the bound for  $\mathbb{E}_{t+1} [\|g^{t+1} - h^{t+1}\|^2]$ :

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \right] \\ & = p_{\text{mega}} \mathbb{E}_{p_a} \left[ \|g_1^{t+1} - h_1^{t+1}\|^2 \right] + (1-p_{\text{mega}}) \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g_2^{t+1} - h_2^{t+1}\|^2 \right] \right]. \end{aligned}$$

867 Using

$$\mathbb{E}_{p_a} [g_{i,1}^{t+1} - h_{i,1}^{t+1}] = g_i^t + k_{i,1}^{t+1} - a(g_i^t - h_i^t) - h_i^t - k_{i,1}^{t+1} = (1-a)(g_i^t - h_i^t)$$

868 and

$$\mathbb{E}_{\mathcal{C}} [\mathbb{E}_{p_a} [g_{i,2}^{t+1} - h_{i,2}^{t+1}]] = g_i^t + k_{i,2}^{t+1} - a(g_i^t - h_i^t) - h_i^t - k_{i,2}^{t+1} = (1-a)(g_i^t - h_i^t),$$

869 we have

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \right] \\ & \stackrel{(14)}{=} p_{\text{mega}} \mathbb{E}_{p_a} \left[ \|g_1^{t+1} - h_1^{t+1} - \mathbb{E}_{p_a} [g_1^{t+1} - h_1^{t+1}]\|^2 \right] \\ & \quad + (1-p_{\text{mega}}) \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \|g_2^{t+1} - h_2^{t+1} - \mathbb{E}_{p_a} [g_2^{t+1} - h_2^{t+1}]\|^2 \right] \right] \\ & \quad + (1-a)^2 \|g^t - h^t\|^2. \end{aligned}$$

870 We can use Lemma 1 two times with i)  $r_i = g_i^t - h_i^t$  and  $s_i = -a(g_i^t - h_i^t)$  and ii)  $r_i = g_i^t - h_i^t$  and

871  $s_i = p_a \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - k_{i,2}^{t+1}$ , to obtain

$$\begin{aligned} & \mathbb{E}_{\mathcal{C}} \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \right] \\ & \leq \frac{p_{\text{mega}} a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \\ & \quad + (1-p_{\text{mega}}) \left( \frac{1}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_{\mathcal{C}} \left[ \left\| p_a \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - (k_{i,2}^{t+1} - a(g_i^t - h_i^t)) \right\|^2 \right] \right) \\ & \quad + (1-p_{\text{mega}}) \left( \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right) \\ & \quad + (1-a)^2 \|g^t - h^t\|^2 \\ & = \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \end{aligned}$$

$$\begin{aligned}
& + (1 - p_{\text{mega}}) \left( \frac{p_a}{n^2} \sum_{i=1}^n \mathbb{E}_C \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right\|^2 \right] \right) \\
& + (1 - a)^2 \|g^t - h^t\|^2 \\
& \leq \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \\
& + \frac{(1 - p_{\text{mega}}) p_a \omega}{n^2} \sum_{i=1}^n \left\| \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right\|^2 \\
& + (1 - a)^2 \|g^t - h^t\|^2 \\
& = \frac{a^2 (p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \\
& + \frac{(1 - p_{\text{mega}}) \omega}{n^2 p_a} \sum_{i=1}^n \|k_{i,2}^{t+1} - a (g_i^t - h_i^t)\|^2 \\
& + (1 - a)^2 \|g^t - h^t\|^2.
\end{aligned}$$

872 In the last inequality, we use Assumption 7. Next, using (13), we have

$$\begin{aligned}
& \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] \right] \right] \\
& \leq \frac{2(1 - p_{\text{mega}}) \omega}{n^2 p_a} \sum_{i=1}^n \|k_{i,2}^{t+1}\|^2 + \left( \frac{(p_a - p_{aa}) a^2}{n^2 p_a^2} + \frac{2(1 - p_{\text{mega}}) \omega a^2}{n^2 p_a} \right) \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \\
& + (1 - a)^2 \|g^t - h^t\|^2.
\end{aligned}$$

873 The second inequality can be proved almost in the same way:

$$\begin{aligned}
& \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \right] \right] \\
& = p_{\text{mega}} \mathbb{E}_{p_a} \left[ \|g_{i,1}^{t+1} - h_{i,1}^{t+1}\|^2 \right] + (1 - p_{\text{mega}}) \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \|g_{i,2}^{t+1} - h_{i,2}^{t+1}\|^2 \right] \right] \\
& \stackrel{(14)}{=} p_{\text{mega}} \mathbb{E}_{p_a} \left[ \|g_{i,1}^{t+1} - h_{i,1}^{t+1} - (1 - a) (g_i^t - h_i^t)\|^2 \right] + (1 - p_{\text{mega}}) \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \|g_{i,2}^{t+1} - h_{i,2}^{t+1}\|^2 \right] \right] \\
& + p_{\text{mega}} (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& = \frac{p_{\text{mega}} (1 - p_a) a^2}{p_a} \|g_i^t - h_i^t\|^2 + (1 - p_{\text{mega}}) \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \|g_{i,2}^{t+1} - h_{i,2}^{t+1}\|^2 \right] \right] \\
& + p_{\text{mega}} (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& \stackrel{(14)}{=} \frac{p_{\text{mega}} (1 - p_a) a^2}{p_a} \|g_i^t - h_i^t\|^2 + (1 - p_{\text{mega}}) \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \|g_{i,2}^{t+1} - h_{i,2}^{t+1} - (1 - a) (g_i^t - h_i^t)\|^2 \right] \right] \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& = \frac{p_{\text{mega}} (1 - p_a) a^2}{p_a} \|g_i^t - h_i^t\|^2 \\
& + (1 - p_{\text{mega}}) p_a \mathbb{E}_C \left[ \left\| g_i^t + \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( h_i^t + \frac{1}{p_a} k_{i,2}^{t+1} \right) - (1 - a) (g_i^t - h_i^t) \right\|^2 \right] \\
& + (1 - p_{\text{mega}}) (1 - p_a) \|g_i^t - h_i^t - (1 - a) (g_i^t - h_i^t)\|^2 \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& = \frac{p_{\text{mega}} (1 - p_a) a^2}{p_a} \|g_i^t - h_i^t\|^2 \\
& + (1 - p_{\text{mega}}) p_a \mathbb{E}_C \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( \frac{1}{p_a} k_{i,2}^{t+1} - a (g_i^t - h_i^t) \right) \right\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + (1 - p_{\text{mega}}) (1 - p_a) a^2 \|g_i^t - h_i^t\|^2 \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& \stackrel{(14)}{=} \left( \frac{p_{\text{mega}}(1 - p_a)a^2}{p_a} + \frac{(1 - p_{\text{mega}})(1 - p_a)a^2}{p_a} \right) \|g_i^t - h_i^t\|^2 \\
& + (1 - p_{\text{mega}}) p_a \mathbb{E} \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right\|^2 \right] \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& = \frac{(1 - p_a)a^2}{p_a} \|g_i^t - h_i^t\|^2 \\
& + (1 - p_{\text{mega}}) p_a \mathbb{E} \left[ \left\| \mathcal{C}_i \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - \left( \frac{1}{p_a} k_{i,2}^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) \right\|^2 \right] \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& \leq \frac{(1 - p_a)a^2}{p_a} \|g_i^t - h_i^t\|^2 \\
& + \frac{(1 - p_{\text{mega}})\omega}{p_a} \|k_{i,2}^{t+1} - a(g_i^t - h_i^t)\|^2 \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2 \\
& \stackrel{(13)}{\leq} \frac{2(1 - p_{\text{mega}})\omega}{p_a} \|k_{i,2}^{t+1}\|^2 + \left( \frac{(1 - p_a)a^2}{p_a} + \frac{2(1 - p_{\text{mega}})a^2\omega}{p_a} \right) \|g_i^t - h_i^t\|^2 \\
& + (1 - a)^2 \|g_i^t - h_i^t\|^2.
\end{aligned}$$

874

□

875 **Lemma 14.** Suppose that Assumptions 3, 5, 6 and 8 hold and let us consider sequence  $\{h_i^{t+1}\}_{i=1}^n$   
876 from Algorithm 8, then

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\
& \leq \frac{2b^2\sigma^2}{np_{\text{mega}}p_a B'} + \left( \frac{2p_{\text{mega}}L_\sigma^2}{np_a B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + \frac{(1 - p_{\text{mega}})L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\hat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \\
& + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{mega}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2,
\end{aligned}$$

877

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\
& \leq \frac{2b^2\sigma^2}{p_a p_{\text{mega}} B'} + \left( \frac{2p_{\text{mega}}L_\sigma^2}{p_a B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + \frac{(1 - p_{\text{mega}})L_\sigma^2}{p_a B} + \frac{2(1 - p_a)L_i^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \\
& + \frac{2(1 - p_a)b^2}{p_{\text{mega}}p_a} \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2, \quad \forall i \in [n],
\end{aligned}$$

878 and

$$\mathbb{E}_k \left[ \|k_{i,2}^{t+1}\|^2 \right] \leq \left( \frac{L_\sigma^2}{B} + L_i^2 \right) \|x^{t+1} - x^t\|^2, \quad \forall i \in [n],$$

879 *Proof.* First, we prove the bound for  $\mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right]$ . Using

$$\mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ h_{i,1}^{t+1} \right] \right]$$

$$\begin{aligned}
&= h_i^t + E_k \left[ \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) - \frac{b}{p_{\text{mega}}} \left( h_i^t - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) \right) \right] \\
&= h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{mega}}} (h_i^t - \nabla f_i(x^t))
\end{aligned}$$

880 and

$$\begin{aligned}
&E_k [E_{p_a} [h_{i,2}^{t+1}]] \\
&= h_i^t + E_k \left[ \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}) \right] \\
&= h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t),
\end{aligned}$$

881 we have

$$\begin{aligned}
&E_k [E_{p_a} [E_{p_{\text{mega}}} [\|h^{t+1} - \nabla f(x^{t+1})\|^2]]] \\
&= p_{\text{mega}} E_k [E_{p_a} [\|h_1^{t+1} - \nabla f(x^{t+1})\|^2]] + (1 - p_{\text{mega}}) E_k [E_{p_a} [\|h_2^{t+1} - \nabla f(x^{t+1})\|^2]] \\
&\stackrel{(14)}{=} p_{\text{mega}} E_k [E_{p_a} [\|h_1^{t+1} - E_k [E_{p_a} [h_1^{t+1}]]\|^2]] + (1 - p_{\text{mega}}) E_k [E_{p_a} [\|h_2^{t+1} - E_k [E_{p_a} [h_2^{t+1}]]\|^2]] \\
&\quad + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2.
\end{aligned}$$

882 We can use Lemma 1 two times with i)  $r_i = h_i^t$  and  $s_i = k_{i,1}^{t+1}$  and ii)  $r_i = h_i^t$  and  $s_i = k_{i,2}^{t+1}$ , to  
883 obtain

$$\begin{aligned}
&E_k [E_{p_a} [E_{p_{\text{mega}}} [\|h^{t+1} - \nabla f(x^{t+1})\|^2]]] \\
&\leq p_{\text{mega}} \left( \frac{1}{n^2 p_a} \sum_{i=1}^n E_k [\|k_{i,1}^{t+1} - E_k [k_{i,1}^{t+1}]\|^2] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{mega}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \right) \\
&\quad + (1 - p_{\text{mega}}) \left( \frac{1}{n^2 p_a} \sum_{i=1}^n E_k [\|k_{i,2}^{t+1} - E_k [k_{i,2}^{t+1}]\|^2] + \frac{p_a - p_{aa}}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \right) \\
&\quad + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2 \\
&\stackrel{(13)}{\leq} \frac{p_{\text{mega}}}{n^2 p_a} \sum_{i=1}^n E_k [\|k_{i,1}^{t+1} - E_k [k_{i,1}^{t+1}]\|^2] \\
&\quad + \frac{1 - p_{\text{mega}}}{n^2 p_a} \sum_{i=1}^n E_k [\|k_{i,2}^{t+1} - E_k [k_{i,2}^{t+1}]\|^2] \\
&\quad + \frac{2(p_a - p_{aa})}{n^2 p_a^2} \sum_{i=1}^n \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
&\quad + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{mega}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2.
\end{aligned} \tag{33}$$

884 Let us consider  $E_k [\|k_{i,1}^{t+1} - E_k [k_{i,1}^{t+1}]\|^2]$ .

$$\begin{aligned}
&E_k [\|k_{i,1}^{t+1} - E_k [k_{i,1}^{t+1}]\|^2] \\
&= E_k \left[ \left\| \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) - \frac{b}{p_{\text{mega}}} \left( h_i^t - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) \right) \right\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& - \left( \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{mega}}} (h_i^t - \nabla f_i(x^t)) \right) \Big\|^2 \Big] \\
& = \mathbb{E}_k \left[ \left\| \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) + \frac{b}{p_{\text{mega}}} \left( \frac{1}{B'} \sum_{k=1}^{B'} \nabla f_i(x^t; \xi_{ik}^{t+1}) \right) \right. \right. \\
& \quad \left. \left. - \left( \nabla f_i(x^{t+1}) - \nabla f_i(x^t) + \frac{b}{p_{\text{mega}}} (\nabla f_i(x^t)) \right) \right\|^2 \right] \\
& = \frac{1}{B'^2} \sum_{k=1}^{B'} \mathbb{E}_k \left[ \left\| \frac{b}{p_{\text{mega}}} (\nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \nabla f_i(x^{t+1})) \right. \right. \\
& \quad \left. \left. + \left( 1 - \frac{b}{p_{\text{mega}}} \right) (\nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \nabla f_i(x^t; \xi_{ik}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))) \right\|^2 \right],
\end{aligned}$$

885 where we used independence of the mini-batch samples. Using (13), we get

$$\begin{aligned}
& \mathbb{E}_k \left[ \left\| k_{i,1}^{t+1} - \mathbb{E}_k [k_{i,1}^{t+1}] \right\|^2 \right] \\
& \leq \frac{2b^2}{B'^2 p_{\text{mega}}^2} \sum_{k=1}^{B'} \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \nabla f_i(x^{t+1}) \right\|^2 \right] \\
& \quad + \frac{2}{B'^2} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 \sum_{k=1}^{B'} \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_{ik}^{t+1}) - \nabla f_i(x^t; \xi_{ik}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right].
\end{aligned}$$

886 Due to Assumptions 5 and 6, we have

$$\mathbb{E}_k \left[ \left\| k_{i,1}^{t+1} - \mathbb{E}_k [k_{i,1}^{t+1}] \right\|^2 \right] \leq \frac{2b^2 \sigma^2}{B' p_{\text{mega}}^2} + \frac{2L_\sigma^2}{B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 \|x^{t+1} - x^t\|^2. \quad (34)$$

887 Next, we estimate the bound for  $\mathbb{E}_k \left[ \left\| k_{i,2}^{t+1} - \mathbb{E}_k [k_{i,2}^{t+1}] \right\|^2 \right]$ .

$$\begin{aligned}
& \mathbb{E}_k \left[ \left\| k_{i,2}^{t+1} - \mathbb{E}_k [k_{i,2}^{t+1}] \right\|^2 \right] \\
& = \mathbb{E}_k \left[ \left\| \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right] \\
& = \frac{1}{B^2} \sum_{j=1}^B \mathbb{E}_k \left[ \left\| \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \nabla f_i(x^t; \xi_{ij}^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)) \right\|^2 \right].
\end{aligned}$$

888 Due to Assumptions 6, we have

$$\mathbb{E}_k \left[ \left\| k_{i,2}^{t+1} - \mathbb{E}_k [k_{i,2}^{t+1}] \right\|^2 \right] \leq \frac{L_\sigma^2}{B} \|x^{t+1} - x^t\|^2. \quad (35)$$

889 Plugging (34) and (35) into (33), we obtain

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\
& \leq \frac{p_{\text{mega}}}{np_a} \left( \frac{2b^2 \sigma^2}{B' p_{\text{mega}}^2} + \frac{2L_\sigma^2}{B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 \|x^{t+1} - x^t\|^2 \right) \\
& \quad + \frac{(1 - p_{\text{mega}}) L_\sigma^2}{np_a B} \|x^{t+1} - x^t\|^2 \\
& \quad + \frac{2(p_a - p_{\text{aa}})}{n^2 p_a^2} \sum_{i=1}^n \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2
\end{aligned}$$

$$+ \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{mega}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2.$$

890 Using Assumption 3, we get

$$\begin{aligned} & \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] \right] \right] \\ & \leq \frac{2b^2 \sigma^2}{n p_{\text{mega}} p_a B'} + \left( \frac{2p_{\text{mega}} L_\sigma^2}{n p_a B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + \frac{(1 - p_{\text{mega}}) L_\sigma^2}{n p_a B} + \frac{2(p_a - p_{aa}) \widehat{L}^2}{n p_a^2} \right) \|x^{t+1} - x^t\|^2 \\ & \quad + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{mega}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2. \end{aligned}$$

891 Using almost the same derivations, we can prove the second inequality:

$$\begin{aligned} & \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\ & = p_{\text{mega}} \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_{i,1}^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] + (1 - p_{\text{mega}}) \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_{i,2}^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \\ & \stackrel{(14)}{=} p_{\text{mega}} \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_{i,1}^{t+1} - \mathbb{E}_k [h_{i,1}^{t+1}]\|^2 \right] \right] + (1 - p_{\text{mega}}) \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \|h_{i,2}^{t+1} - \mathbb{E}_k [h_{i,2}^{t+1}]\|^2 \right] \right] \\ & \quad + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\ & = p_{\text{mega}} p_a \mathbb{E}_k \left[ \left\| h_i^t + \frac{1}{p_a} k_{i,1}^{t+1} - (h_i^t + \mathbb{E}_k [k_{i,1}^{t+1}]) \right\|^2 \right] \\ & \quad + p_{\text{mega}} (1 - p_a) \|h_i^t - (h_i^t + \mathbb{E}_k [k_{i,1}^{t+1}])\|^2 \\ & \quad + (1 - p_{\text{mega}}) p_a \mathbb{E}_k \left[ \left\| h_i^t + \frac{1}{p_a} k_{i,2}^{t+1} - (h_i^t + \mathbb{E}_k [k_{i,2}^{t+1}]) \right\|^2 \right] \\ & \quad + (1 - p_{\text{mega}}) (1 - p_a) \|h_i^t - (h_i^t + \mathbb{E}_k [k_{i,2}^{t+1}])\|^2 \\ & \quad + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\ & = p_{\text{mega}} p_a \mathbb{E}_k \left[ \left\| \frac{1}{p_a} k_{i,1}^{t+1} - \mathbb{E}_k [k_{i,1}^{t+1}] \right\|^2 \right] \\ & \quad + p_{\text{mega}} (1 - p_a) \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{mega}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\ & \quad + (1 - p_{\text{mega}}) p_a \mathbb{E}_k \left[ \left\| \frac{1}{p_a} k_{i,2}^{t+1} - \mathbb{E}_k [k_{i,2}^{t+1}] \right\|^2 \right] \\ & \quad + (1 - p_{\text{mega}}) (1 - p_a) \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\ & \quad + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\ & \stackrel{(14)}{=} \frac{p_{\text{mega}}}{p_a} \mathbb{E}_k \left[ \|k_{i,1}^{t+1} - \mathbb{E}_k [k_{i,1}^{t+1}]\|^2 \right] \\ & \quad + \frac{(1 - p_{\text{mega}})}{p_a} \mathbb{E}_k \left[ \|k_{i,2}^{t+1} - \mathbb{E}_k [k_{i,2}^{t+1}]\|^2 \right] \\ & \quad + \frac{p_{\text{mega}} (1 - p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{mega}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\ & \quad + \frac{(1 - p_{\text{mega}}) (1 - p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \end{aligned}$$

$$\begin{aligned}
& + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\
& \stackrel{(13)}{\leq} \frac{p_{\text{mega}}}{p_a} \mathbb{E}_k \left[ \|k_{i,1}^{t+1} - \mathbb{E}_k[k_{i,1}^{t+1}]\|^2 \right] \\
& + \frac{(1 - p_{\text{mega}})}{p_a} \mathbb{E}_k \left[ \|k_{i,2}^{t+1} - \mathbb{E}_k[k_{i,2}^{t+1}]\|^2 \right] \\
& + \frac{2(1 - p_a)}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
& + \frac{2(1 - p_a)b^2}{p_{\text{mega}}p_a} \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

892 Using (34) and (35), we get

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\
& \leq \frac{2b^2\sigma^2}{p_ap_{\text{mega}}B'} + \frac{2p_{\text{mega}}L_\sigma^2}{p_aB'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 \|x^{t+1} - x^t\|^2 \\
& + \frac{(1 - p_{\text{mega}})L_\sigma^2}{p_aB} \|x^{t+1} - x^t\|^2 \\
& + \frac{2(1 - p_a)}{p_a} \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
& + \frac{2(1 - p_a)b^2}{p_{\text{mega}}p_a} \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

893 Next, due to Assumption 3, we obtain

$$\begin{aligned}
& \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\
& \leq \frac{2b^2\sigma^2}{p_ap_{\text{mega}}B'} + \left( \frac{2p_{\text{mega}}L_\sigma^2}{p_aB'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + \frac{(1 - p_{\text{mega}})L_\sigma^2}{p_aB} + \frac{2(1 - p_a)L_i^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \\
& + \frac{2(1 - p_a)b^2}{p_{\text{mega}}p_a} \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1 - p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2.
\end{aligned}$$

894 The third inequality can be proved with the help of (35) and Assumption 3.

$$\begin{aligned}
& \mathbb{E}_k \left[ \|k_{i,2}^{t+1}\|^2 \right] \\
& \stackrel{(14)}{=} \mathbb{E}_k \left[ \|k_{i,2}^{t+1} - \mathbb{E}_k[k_{i,2}^{t+1}]\|^2 \right] + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
& \leq \frac{L_\sigma^2}{B} \|x^{t+1} - x^t\|^2 + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 \\
& \leq \left( \frac{L_\sigma^2}{B} + L_i^2 \right) \|x^{t+1} - x^t\|^2.
\end{aligned}$$

895

□

**Theorem 11.** Suppose that Assumptions 1, 2, 3, 5, 6, 7 and 8 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_{\text{mega}}p_a}{2-p_a}$ , probability  $p_{\text{mega}} \in (0, 1]$ , batch size  $B' \geq B \geq 1$

$$\gamma \leq \left( L + \sqrt{\frac{8(2\omega+1)\omega}{np_a^2} \left( \widehat{L}^2 + \frac{L_\sigma^2}{B} \right) + \frac{16}{np_{\text{mega}}p_a^2} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \widehat{L}^2 + \frac{L_\sigma^2}{B} \right)} \right)^{-1},$$

896 and  $h_i^0 = g_i^0$  for all  $i \in [n]$  in Algorithm 8. Then

$$\mathbb{E} \left[ \|\nabla f(\widehat{x}^T)\|^2 \right] \leq \frac{1}{T} \left[ \frac{2\Delta_0}{\gamma} + \frac{4}{p_{\text{mega}}p_a} \|h^0 - \nabla f(x^0)\|^2 + \frac{4 \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_{\text{mega}}p_a} \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right]$$



$$+ \frac{12\sigma^2}{nB'}.$$

897 *Proof.* Due to Lemma 2 and the update step from Line 4 in Algorithm 8, we have

$$\begin{aligned} & \mathbb{E}_{t+1} [f(x^{t+1})] \\ & \leq \mathbb{E}_{t+1} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \frac{\gamma}{2} \|g^t - \nabla f(x^t)\|^2 \right] \\ & = \mathbb{E}_{t+1} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \frac{\gamma}{2} \|g^t - h^t + h^t - \nabla f(x^t)\|^2 \right] \\ & \stackrel{(14)}{\leq} \mathbb{E}_{t+1} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \left( \|g^t - h^t\|^2 + \|h^t - \nabla f(x^t)\|^2 \right) \right]. \end{aligned}$$

898 Let us fix constants  $\kappa, \eta, \nu, \rho \in [0, \infty)$  that we will define later. Considering Lemma 13, Lemma 14,  
899 and the law of total expectation, we obtain

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \kappa \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & \quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \left( \|g^t - h^t\|^2 + \|h^t - \nabla f(x^t)\|^2 \right) \right] \\ & \quad + \kappa \mathbb{E} \left[ \mathbb{E}_k \left[ \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} [\|g^{t+1} - h^{t+1}\|^2] \right] \right] \right] \right] \\ & \quad + \eta \mathbb{E} \left[ \mathbb{E}_k \left[ \mathbb{E}_C \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \right] \right] \right] \right] \\ & \quad + \nu \mathbb{E} \left[ \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] \right] \right] \right] \\ & \quad + \rho \mathbb{E} \left[ \mathbb{E}_k \left[ \mathbb{E}_{p_a} \left[ \mathbb{E}_{p_{\text{mega}}} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma \left( \|g^t - h^t\|^2 + \|h^t - \nabla f(x^t)\|^2 \right) \right] \\ & \quad + \kappa \mathbb{E} \left( \frac{2(1-p_{\text{mega}})\omega}{np_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + \left( \frac{(p_a - p_{aa})a^2}{n^2 p_a^2} + \frac{2(1-p_{\text{mega}})a^2\omega}{n^2 p_a} \right) \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \right) \\ & \quad + \eta \mathbb{E} \left( \frac{2(1-p_{\text{mega}})\omega}{p_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + \left( \frac{(1-p_a)a^2}{p_a} + \frac{2(1-p_{\text{mega}})a^2\omega}{p_a} \right) \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \right) \\ & \quad + \nu \mathbb{E} \left( \frac{2b^2\sigma^2}{np_{\text{mega}}p_a B'} + \left( \frac{2p_{\text{mega}}L_\sigma^2}{np_a B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + \frac{(1-p_{\text{mega}})L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2 p_a^2 p_{\text{mega}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1-p_{\text{mega}}) \right) \|h^t - \nabla f(x^t)\|^2 \right) \\ & \quad + \rho \mathbb{E} \left( \frac{2b^2\sigma^2}{p_a p_{\text{mega}} B'} + \left( \frac{2p_{\text{mega}}L_\sigma^2}{p_a B'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + \frac{(1-p_{\text{mega}})L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \right) \end{aligned}$$

$$+ \frac{2(1-p_a)b^2}{np_{\text{mega}}p_a} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + \left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1-p_{\text{mega}}) \right) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \Bigg).$$

Let us simplify the last inequality. Since  $B' \geq B$  and  $b = \frac{p_{\text{mega}}p_a}{2-p_a} \leq p_{\text{mega}}$ , we have  $1 - p_{\text{mega}} \leq 1$ ,

$$\frac{2p_{\text{mega}}L_\sigma^2}{p_aB'} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 \leq \frac{2p_{\text{mega}}L_\sigma^2}{p_aB},$$

$$\left( p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1-p_{\text{mega}}) \right) \leq 1 - b,$$

and

$$\left( \frac{2(1-p_a)b^2}{p_{\text{mega}}p_a} + p_{\text{mega}} \left( 1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1-p_{\text{mega}}) \right) \leq 1 - b.$$

900 Thus

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \kappa \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} \left[ f(x^t) - \frac{\gamma}{2} \|\nabla f(x^t)\|^2 - \left( \frac{1}{2\gamma} - \frac{L}{2} \right) \|x^{t+1} - x^t\|^2 + \gamma (\|g^t - h^t\|^2 + \|h^t - \nabla f(x^t)\|^2) \right] \\ & + \kappa \mathbb{E} \left( \frac{2\omega}{np_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + \frac{((2\omega+1)p_a - p_{aa})a^2}{n^2p_a^2} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \right) \\ & + \eta \mathbb{E} \left( \frac{2\omega}{p_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + \frac{(2\omega+1-p_a)a^2}{p_a} \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 + (1-a)^2 \|g^t - h^t\|^2 \right) \\ & + \nu \mathbb{E} \left( \frac{2b^2\sigma^2}{np_{\text{mega}}p_aB'} + \left( \frac{2L_\sigma^2}{np_aB} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + \frac{2(p_a - p_{aa})b^2}{n^2p_a^2p_{\text{mega}}} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 + (1-b) \|h^t - \nabla f(x^t)\|^2 \right) \\ & + \rho \mathbb{E} \left( \frac{2b^2\sigma^2}{p_ap_{\text{mega}}B'} + \left( \frac{2L_\sigma^2}{p_aB} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \right. \\ & \quad \left. + (1-b) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right). \end{aligned}$$

901 After rearranging the terms, we get

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \kappa \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \end{aligned}$$

$$\begin{aligned}
&\leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{2\kappa\omega}{np_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \frac{2\eta\omega}{p_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
&\quad \left. - \nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
&\quad + (\gamma + \kappa(1-a)^2) \mathbb{E} [\|g^t - h^t\|^2] \\
&\quad + \left( \kappa \frac{((2\omega+1)p_a - p_{aa})a^2}{np_a^2} + \eta \left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&\quad + (\gamma + \nu(1-b)) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
&\quad + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
&\quad + \left( \frac{2\nu b^2}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'}.
\end{aligned}$$

902 Let us take  $\kappa = \frac{\gamma}{a}$ , thus  $\gamma + \kappa(1-a)^2 \leq \kappa$  and

$$\begin{aligned}
&\mathbb{E} [f(x^{t+1})] + \frac{\gamma}{a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
&\quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
&\leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{2\gamma\omega}{anp_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \frac{2\eta\omega}{p_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
&\quad \left. - \nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
&\quad + \frac{\gamma}{a} \mathbb{E} [\|g^t - h^t\|^2] \\
&\quad + \left( \frac{\gamma((2\omega+1)p_a - p_{aa})a}{np_a^2} + \eta \left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&\quad + (\gamma + \nu(1-b)) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
&\quad + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
&\quad + \left( \frac{2\nu b^2}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'}.
\end{aligned}$$

903 Next, since  $a = \frac{p_a}{2\omega+1}$ , we have  $\left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \leq 1-a$ . We the choice  $\eta =$

904  $\frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2}$ , we guarantee  $\frac{\gamma((2\omega+1)p_a - p_{aa})a}{np_a^2} + \eta \left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \leq \eta$  and

$$\begin{aligned}
&\mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
&\quad + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
&\leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{2\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \frac{2\gamma((2\omega+1)p_a - p_{aa})\omega}{np_a^3} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
&\quad \left. - \nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
&\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&\quad + (\gamma + \nu(1-b)) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
&\quad + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
&\quad + \left( \frac{2\nu b^2}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'} \\
&\leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
&\quad \left. - \nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
&\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&\quad + (\gamma + \nu(1-b)) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\
&\quad + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
&\quad + \left( \frac{2\nu b^2}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'},
\end{aligned}$$

905 where simplified the term using  $p_{aa} \geq 0$ . Let us take  $\nu = \frac{\gamma}{b}$  to obtain

$$\begin{aligned}
&\mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
&\quad + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
&\leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
&\quad - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
&\quad \left. - \left( \frac{2\gamma L_\sigma^2}{bn p_a B} + \frac{2\gamma(p_a - p_{aa})\widehat{L}^2}{bn p_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
&\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&\quad + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2]
\end{aligned}$$

$$\begin{aligned}
& + \left( \frac{2\gamma(p_a - p_{aa})b}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{2\gamma b}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'}.
\end{aligned}$$

906 Next, we take  $\rho = \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}}$ , thus

$$\begin{aligned}
& \mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma(2\omega + 1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \hat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{2\gamma L_\sigma^2}{bn p_a B} + \frac{2\gamma(p_a - p_{aa})\hat{L}^2}{bn p_a^2} \right) - \left( \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \right) \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\hat{L}^2}{p_a} \right) \right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{2\gamma b}{np_{\text{mega}} p_a} + \frac{4\gamma(p_a - p_{aa})b^2}{np_a^3 p_{\text{mega}}} \right) \frac{\sigma^2}{B'}.
\end{aligned}$$

907 Since  $\frac{p_{\text{mega}} p_a}{2} \leq b \leq p_{\text{mega}} p_a$  and  $1 - p_a \leq 1 - \frac{p_{aa}}{p_a} \leq 1$ , we get

$$\begin{aligned}
& \mathbb{E}[f(x^{t+1})] + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma(2\omega + 1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \hat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{4\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{4\gamma(p_a - p_{aa})\hat{L}^2}{np_{\text{mega}} p_a^3} \right) - \left( \frac{4\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{4\gamma(1-p_a)\hat{L}^2}{np_{\text{mega}} p_a^2} \right) \right) \mathbb{E}[\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma(2\omega + 1)}{p_a} \mathbb{E}[\|g^t - h^t\|^2] + \frac{\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E}[\|h^t - \nabla f(x^t)\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{6\gamma\sigma^2}{nB'} \\
& \leq \mathbb{E}[f(x^t)] - \frac{\gamma}{2} \mathbb{E}[\|\nabla f(x^t)\|^2]
\end{aligned}$$

$$\begin{aligned}
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \left( \frac{8\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{8\gamma \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2}{np_{\text{mega}} p_a^2} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{6\gamma\sigma^2}{nB'}.
\end{aligned}$$

908 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \frac{\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \frac{2\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{6\gamma\sigma^2}{nB'}.
\end{aligned}$$

909 It is left to apply Lemma 3 with

$$\begin{aligned}
\Psi^t &= \frac{(2\omega+1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \frac{((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
&+ \frac{1}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \frac{2 \left(1 - \frac{p_{aa}}{p_a}\right)}{np_a p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right]
\end{aligned}$$

910 and  $C = \frac{6\sigma^2}{nB'}$  to conclude the proof.  $\square$

**Corollary 6.** Suppose that assumptions from Theorem 11 hold, probability  $p_{\text{mega}} = \min \left\{ \frac{\zeta_C}{d}, \frac{n\varepsilon B}{\sigma^2} \right\}$ , batch size  $B' = \Theta \left( \frac{\sigma^2}{n\varepsilon} \right)$ , and  $h_i^0 = g_i^0 = \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0)$  for all  $i \in [n]$ , initial batch size  $B_{\text{init}} = \Theta \left( \frac{B}{p_{\text{mega}} \sqrt{p_a}} \right) = \Theta \left( \max \left\{ \frac{Bd}{\sqrt{p_a} \zeta_C}, \frac{\sigma^2}{\sqrt{p_a} n\varepsilon} \right\} \right)$ , then DASHA-PP-SYNC-MVR needs

$$T := \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \left( \frac{\omega}{p_a \sqrt{n}} + \sqrt{\frac{d}{p_a^2 \zeta_C n}} \right) \left( \widehat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a \sqrt{\varepsilon} n} \left( \frac{\widehat{L}}{\sqrt{B}} + \frac{L_\sigma}{B} \right) \right] + \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} \right).$$

911 communication rounds to get an  $\varepsilon$ -solution, the expected communication complexity is equal to  
912  $\mathcal{O}(d + \zeta_C T)$ , and the expected number of stochastic gradient calculations per node equals  $\mathcal{O}(B_{\text{init}} +$   
913  $BT)$ , where  $\zeta_C$  is the expected density from Definition 12.

914 *Proof.* Due to the choice of  $B'$ , we have

$$\begin{aligned} \mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] &\leq \frac{1}{T} \left[ 2\Delta_0 \left( L + \sqrt{\frac{8(2\omega+1)\omega}{np_a^2} \left( \hat{L}^2 + \frac{L_\sigma^2}{B} \right) + \frac{16}{np_{\text{mega}}p_a^2} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{L_\sigma^2}{B} \right)} \right) \right. \\ &\quad \left. + \frac{4}{p_{\text{mega}}p_a} \|h^0 - \nabla f(x^0)\|^2 + \frac{4 \left( 1 - \frac{p_{aa}}{p_a} \right)}{np_{\text{mega}}p_a} \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right] \\ &\quad + \frac{2\varepsilon}{3}. \end{aligned}$$

915 Using

$$\mathbb{E} \left[ \|h^0 - \nabla f(x^0)\|^2 \right] = \mathbb{E} \left[ \left\| \frac{1}{n} \sum_{i=1}^n \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0) - \nabla f(x^0) \right\|^2 \right] \leq \frac{\sigma^2}{nB_{\text{init}}}$$

916 and

$$\frac{1}{n^2} \sum_{i=1}^n \mathbb{E} \left[ \|h_i^0 - \nabla f_i(x^0)\|^2 \right] = \frac{1}{n^2} \sum_{i=1}^n \mathbb{E} \left[ \left\| \frac{1}{B_{\text{init}}} \sum_{k=1}^{B_{\text{init}}} \nabla f_i(x^0; \xi_{ik}^0) - \nabla f_i(x^0) \right\|^2 \right] \leq \frac{\sigma^2}{nB_{\text{init}}},$$

917 we have

$$\begin{aligned} \mathbb{E} \left[ \|\nabla f(\hat{x}^T)\|^2 \right] &\leq \frac{1}{T} \left[ 2\Delta_0 \left( L + \sqrt{\frac{8(2\omega+1)\omega}{np_a^2} \left( \hat{L}^2 + \frac{L_\sigma^2}{B} \right) + \frac{16}{np_{\text{mega}}p_a^2} \left( \left( 1 - \frac{p_{aa}}{p_a} \right) \hat{L}^2 + \frac{L_\sigma^2}{B} \right)} \right) \right. \\ &\quad \left. + \frac{8\sigma^2}{np_{\text{mega}}p_a B_{\text{init}}} \right] \\ &\quad + \frac{2\varepsilon}{3}. \end{aligned}$$

918 Therefore, we can take the following  $T$  to get  $\varepsilon$ -solution.

$$T = \mathcal{O} \left( \frac{1}{\varepsilon} \left[ \Delta_0 \left( L + \sqrt{\frac{\omega^2}{np_a^2} \left( \hat{L}^2 + \frac{L_\sigma^2}{B} \right) + \frac{1}{np_{\text{mega}}p_a^2} \left( \hat{L}^2 + \frac{L_\sigma^2}{B} \right)} \right) + \frac{\sigma^2}{np_{\text{mega}}p_a B_{\text{init}}} \right] \right)$$

919 Considering the choice of  $p_{\text{mega}}$  and  $B_{\text{init}}$ , we obtain

$$\begin{aligned} T &= \mathcal{O} \left( \frac{1}{\varepsilon} \left[ \Delta_0 \left( L + \left( \frac{\omega}{p_a \sqrt{n}} + \sqrt{\frac{d}{p_a^2 \zeta_C n}} \right) \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a \sqrt{\varepsilon n}} \left( \frac{\hat{L}}{\sqrt{B}} + \frac{L_\sigma}{B} \right) \right) + \frac{\sigma^2}{np_{\text{mega}}p_a B_{\text{init}}} \right] \right) \\ &= \mathcal{O} \left( \frac{\Delta_0}{\varepsilon} \left[ L + \left( \frac{\omega}{p_a \sqrt{n}} + \sqrt{\frac{d}{p_a^2 \zeta_C n}} \right) \left( \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a \sqrt{\varepsilon n}} \left( \frac{\hat{L}}{\sqrt{B}} + \frac{L_\sigma}{B} \right) \right] + \frac{\sigma^2}{\sqrt{p_a} n \varepsilon B} \right). \end{aligned}$$

920 The expected communication complexity equals  $\mathcal{O}(d + p_{\text{mega}}d + (1 - p_{\text{mega}})\zeta_C) =$   
 921  $\mathcal{O}(d + \zeta_C)$  and the expected number of stochastic gradient calculations per node equals  
 922  $\mathcal{O}(B_{\text{init}} + p_{\text{mega}}B' + (1 - p_{\text{mega}})B) = \mathcal{O}(B_{\text{init}} + B)$ .  $\square$

**Theorem 13.** Suppose that Assumptions 1, 2, 3, 5, 6, 7, 8 and 9 hold. Let us take  $a = \frac{p_a}{2\omega+1}$ ,  $b = \frac{p_{\text{mega}}p_a}{2-p_a}$ , probability  $p_{\text{mega}} \in (0, 1]$ , batch size  $B' \geq B \geq 1$ ,

$$\gamma \leq \min \left\{ \left( L + \sqrt{\frac{16(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) + \left( \frac{48L_\sigma^2}{np_{\text{mega}}p_a^2B} + \frac{24 \left( 1 - \frac{p_{aa}}{p_a} \right) \widehat{L}^2}{np_{\text{mega}}p_a^2} \right)} \right)^{-1}, \frac{a}{2\mu}, \frac{b}{2\mu} \right\},$$

923 and  $h_i^0 = g_i^0$  for all  $i \in [n]$  in Algorithm 8. Then

$$\begin{aligned} & \mathbb{E} [f(x^T) - f^*] \\ & \leq (1 - \gamma\mu)^T \left( \Delta_0 + \frac{2\gamma}{b} \|h^0 - \nabla f(x^0)\|^2 + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) + \frac{20\sigma^2}{\mu n B'}. \end{aligned}$$

924 *Proof.* Let us fix constants  $\kappa, \eta, \nu, \rho \in [0, \infty)$  that we will define later. As in the proof of Theorem 11,  
925 we can get

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \kappa \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\ & - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{2\kappa\omega}{np_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \frac{2\eta\omega}{p_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\ & \quad \left. - \nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\ & + (\gamma + \kappa(1-a)^2) \mathbb{E} [\|g^t - h^t\|^2] \\ & + \left( \kappa \frac{((2\omega+1)p_a - p_{aa})a^2}{np_a^2} + \eta \left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ & + (\gamma + \nu(1-b)) \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] \\ & + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\ & + \left( \frac{2\nu b^2}{np_{\text{mega}}p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'}. \end{aligned}$$

926 Let us take  $\kappa = \frac{2\gamma}{a}$ , thus  $\gamma + \kappa(1-a)^2 \leq (1 - \frac{a}{2})\kappa$  and

$$\begin{aligned} & \mathbb{E} [f(x^{t+1})] + \frac{2\gamma}{a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \eta \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\ & + \nu \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\ & \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\ & - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{4\gamma\omega}{anp_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \frac{2\eta\omega}{p_a} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \end{aligned}$$



$$\begin{aligned}
& -\nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma}{a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] \\
& + \left( \frac{2\gamma((2\omega+1)p_a - p_{aa})a}{np_a^2} + \eta \left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + (\gamma + \nu(1-b)) \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{2\nu b^2}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'}.
\end{aligned}$$

927 Next, since  $a = \frac{p_a}{2\omega+1}$ , we have  $\left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \leq 1-a$ . We the choice  $\eta =$   
928  $\frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2}$ , we guarantee  $\frac{\gamma((2\omega+1)p_a - p_{aa})a}{np_a^2} + \eta \left( \frac{(2\omega+1-p_a)a^2}{p_a} + (1-a)^2 \right) \leq (1-\frac{a}{2})\eta$  and

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \nu \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
& \quad \left. - \nu \left( \frac{2L_\sigma^2}{np_a B} + \frac{2(p_a - p_{aa})\widehat{L}^2}{np_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + (\gamma + \nu(1-b)) \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( \nu \frac{2(p_a - p_{aa})b^2}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{2\nu b^2}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'},
\end{aligned}$$

929 where simplified the term using  $p_{aa} \geq 0$ . Let us take  $\nu = \frac{2\gamma}{b}$  to obtain

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \rho \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{4\gamma L_\sigma^2}{bnp_a B} + \frac{4\gamma(p_a - p_{aa})\widehat{L}^2}{bnp_a^2} \right) - \rho \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \left( 1 - \frac{a}{2} \right) \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( 1 - \frac{b}{2} \right) \frac{2\gamma}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] \\
& + \left( \frac{4\gamma(p_a - p_{aa})b}{np_a^2 p_{\text{mega}}} + \rho(1-b) \right) \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{4\gamma b}{np_{\text{mega}} p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'},
\end{aligned}$$

930 Next, we take  $\rho = \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}}$ , thus

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{4\gamma L_\sigma^2}{bnp_a B} + \frac{4\gamma(p_a - p_{aa})\widehat{L}^2}{bnp_a^2} \right) - \left( \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \right) \left( \frac{2L_\sigma^2}{p_a B} + \frac{2(1-p_a)\widehat{L}^2}{p_a} \right) \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right] \\
& + \left( 1 - \frac{a}{2} \right) \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \left( 1 - \frac{a}{2} \right) \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left( 1 - \frac{b}{2} \right) \frac{2\gamma}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] + \left( 1 - \frac{b}{2} \right) \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \left( \frac{4\gamma b}{np_{\text{mega}} p_a} + \frac{16\gamma(p_a - p_{aa})b^2}{np_a^3 p_{\text{mega}}^2} \right) \frac{\sigma^2}{B'},
\end{aligned}$$

931 Since  $\frac{p_{\text{mega}} p_a}{2} \leq b \leq p_{\text{mega}} p_a$  and  $1 - p_a \leq 1 - \frac{p_{aa}}{p_a} \leq 1$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega+1)}{p_a} \mathbb{E} \left[ \|g^{t+1} - h^{t+1}\|^2 \right] + \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} \left[ \|h^{t+1} - \nabla f(x^{t+1})\|^2 \right] + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
& \leq \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} \left[ \|\nabla f(x^t)\|^2 \right] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma(2\omega+1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) \right. \\
& \quad \left. - \left( \frac{8\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{8\gamma(p_a - p_{aa})\widehat{L}^2}{np_{\text{mega}} p_a^3} \right) - \left( \frac{16\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{16\gamma(1-p_a)\widehat{L}^2}{np_{\text{mega}} p_a^2} \right) \right) \mathbb{E} \left[ \|x^{t+1} - x^t\|^2 \right]
\end{aligned}$$

$$\begin{aligned}
& + \left(1 - \frac{a}{2}\right) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \left(1 - \frac{a}{2}\right) \frac{2\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{20\gamma\sigma^2}{nB'} \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& - \left( \frac{1}{2\gamma} - \frac{L}{2} - \frac{8\gamma(2\omega + 1)\omega}{np_a^2} \left( \frac{L_\sigma^2}{B} + \widehat{L}^2 \right) - \left( \frac{24\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{24\gamma \left(1 - \frac{p_{aa}}{p_a}\right) \widehat{L}^2}{np_{\text{mega}} p_a^2} \right) \right) \mathbb{E} [\|x^{t+1} - x^t\|^2] \\
& + \left(1 - \frac{a}{2}\right) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \left(1 - \frac{a}{2}\right) \frac{2\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{20\gamma\sigma^2}{nB'}.
\end{aligned}$$

932 Using Lemma 4 and the assumption about  $\gamma$ , we get

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{2\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + \left(1 - \frac{a}{2}\right) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + \left(1 - \frac{a}{2}\right) \frac{2\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + \left(1 - \frac{b}{2}\right) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + \left(1 - \frac{b}{2}\right) \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{20\gamma\sigma^2}{nB'}.
\end{aligned}$$

933 Due to  $\gamma \leq \frac{a}{2\mu}$  and  $\gamma \leq \frac{b}{2\mu}$ , we have

$$\begin{aligned}
& \mathbb{E} [f(x^{t+1})] + \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^{t+1} - h^{t+1}\|^2] + \frac{2\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^{t+1} - h_i^{t+1}\|^2 \right] \\
& + \frac{2\gamma}{b} \mathbb{E} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] + \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \\
\leq & \mathbb{E} [f(x^t)] - \frac{\gamma}{2} \mathbb{E} [\|\nabla f(x^t)\|^2] \\
& + (1 - \gamma\mu) \frac{2\gamma(2\omega + 1)}{p_a} \mathbb{E} [\|g^t - h^t\|^2] + (1 - \gamma\mu) \frac{2\gamma((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\
& + (1 - \gamma\mu) \frac{2\gamma}{b} \mathbb{E} [\|h^t - \nabla f(x^t)\|^2] + (1 - \gamma\mu) \frac{8\gamma(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right] \\
& + \frac{20\gamma\sigma^2}{nB'}.
\end{aligned}$$

934 It is left to apply Lemma 11 with

$$\begin{aligned}\Psi^t &= \frac{2(2\omega + 1)}{p_a} \mathbb{E} \left[ \|g^t - h^t\|^2 \right] + \frac{2((2\omega + 1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|g_i^t - h_i^t\|^2 \right] \\ &+ \frac{2}{b} \mathbb{E} \left[ \|h^t - \nabla f(x^t)\|^2 \right] + \frac{8(p_a - p_{aa})}{np_a^2 p_{\text{mega}}} \mathbb{E} \left[ \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \right]\end{aligned}$$

935 and  $C = \frac{20\sigma^2}{nB'}$  to conclude the proof. □