

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

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Abstract

We present a new method that includes three key components of distributed optimization and federated learning: variance reduction of stochastic gradients, partial participation, and compressed communication. We prove that the new method has optimal oracle complexity and state-of-the-art communication complexity in the partial participation setting. Even without the communication compression feature, our method successfully combines variance reduction and partial participation: we get the optimal oracle complexity, never need the participation of all nodes, and do not require the bounded gradients (dissimilarity) assumption.

1. Introduction

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

As in classical optimization tasks, one of the main current challenges is to find **computationally efficient** optimization algorithms. However, the nature of distributed problems induces many other (Kairouz et al., 2021), including i) **partial participation** of nodes in algorithm steps: due to stragglers (Li et al., 2020) or communication delays (Vogels et al.,

2021), ii) **communication bottleneck**: even if a node participates, it can be costly to transmit information to a server or other nodes (Alistarh et al., 2017; Ramesh et al., 2021; Kairouz et al., 2021; Sapio et al., 2019; Narayanan et al., 2019). It is necessary to develop a method that considers these problems.

2. Optimization Problem

Let us consider the nonconvex distributed optimization problem

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

where $f_i : \mathbb{R}^d \rightarrow \mathbb{R}$ is a smooth nonconvex function for all $i \in [n] := \{1, \dots, n\}$. The full information about function f_i is stored on i^{th} node. The communication between nodes is maintained 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.¹ Since we work in the nonconvex world, our goal is to find an ε -solution (ε -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^{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 $\hat{L}^2 := \frac{1}{n} \sum_{i=1}^n L_i^2$.²*

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¹Note 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.

²Note 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
SPIDER, SARAH, PAGE, STORM (Fang et al., 2018; Nguyen et al., 2017) (Li et al., 2021a; Cutkosky & Orabona, 2019)	✓	✗	✗	—
MARINA (Gorbunov et al., 2021)	✓	✗ ^(a)	✓ ^(b)	Suboptimal convergence rate (see (Tyurin & Richtárik, 2023)).
FedPAGE (Zhao et al., 2021b)	✗	✗ ^(a)	✗	Suboptimal oracle complexity $\mathcal{O}\left(\frac{\sigma^2}{\varepsilon^2}\right)$.
FRECON (Zhao et al., 2021a)	✗	✓	✓	—
FedAvg (McMahan et al., 2017; Karimireddy et al., 2020b)	✗	✓	✗	Bounded gradients (dissimilarity) assumption of f_i .
SCAFFOLD (Karimireddy et al., 2020b)	✗	✓	✗	Suboptimal convergence rate ^(e) .
MIME^(c) (Karimireddy et al., 2020a)	✗ ^(d)	✓	✗	Calculates full gradient. Bounded gradients (dissimilarity) assumption of f_i . Do not support the finite-sum setting (2).
CE-LSGD (for Partial Participation)^(c) (Patel et al., 2022) (concurrent work)	✓	✓	✗	Bounded gradients (dissimilarity) assumption of f_i . Do not support the finite-sum setting (2).
DASHA (Tyurin & Richtárik, 2023)	✓ ✗	✗ or ✓	✓ ✓	—
DASHA-PP (new)	✓	✓	✓	—

^(a) **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.

^(b) 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.

^(c) 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.

^(d) 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.

^(e) 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 ε -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 $p_a = \frac{s}{n}$).

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

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

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,

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

^(a), ^(b) : see Table 1.

for a fixed $\xi \in \Omega_\xi$, $f_i(x; \xi)$ is a smooth nonconvex function. The i^{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 ξ_{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 ε -solution, and the communication complexity, i.e., the number of bits that each node has to send to the server to get ε -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 $x \in \mathbb{R}^d$.

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 independent.

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. $p_{aa} \leq p_a^2,$ (5)

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 & 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 $\mathcal{O}(1/\epsilon)$, 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 $\mathcal{O}\left(m + \frac{\sqrt{m}}{\epsilon}\right)$ and $\mathcal{O}\left(\frac{\sigma^2}{\epsilon} + \frac{\sigma}{\epsilon^{3/2}}\right)$ (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 & 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 & 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 & Richtárik, 2023). In the gradient setting, the methods MARINA and DASHA by (Gorbunov et al., 2021) and (Tyurin & Richtárik, 2023) establish the current SOTA communication complexity, each method needs $\frac{1+\omega/\sqrt{n}}{\epsilon}$ communication rounds to get an ϵ -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 $\mathcal{O}\left(m + \frac{\sqrt{m}}{\epsilon\sqrt{n}}\right)$ and $\mathcal{O}\left(\frac{\sigma^2}{\epsilon n} + \frac{\sigma}{\epsilon^{3/2}n}\right)$ 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 & 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. Also, MIME and CE-LSGD (for Partial Participation) do not support the finite-sum setting (2).

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.

5. Algorithm Description

We now present **DASHA-PP** (see Algorithm 1), a family of methods to solve the optimization problem (1). **DASHA-PP** is based on **DASHA**. One can easily show that **DASHA-PP** reduces to **DASHA** when $p_a = 1$. The refinement of **DASHA** is not an exercise, let us point out the main differences:

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_{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 .

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 ε -solution after T communication rounds. Then, ideally, we would expect the convergence of the new algorithms to ε -solution after up to T/p_a communication rounds due to the partial participation

constraints³. The detailed analysis of the algorithms under Polyak-Łojasiewicz condition we provide in Section D. Let us define $\Delta_0 := f(x^0) - f^*$.

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 ε -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 $a = \frac{p_a}{2\omega+1}$, $b = \frac{p_{\text{page}} p_a}{2-p_a}$, probability $p_{\text{page}} \in (0, 1]$,

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

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 $p_{\text{page}} = B/(m+B)$. 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 ε -solution and the expected number of gradient calculations per node equals $\mathcal{O}(m + BT)$.

³We check this numerically in Section A.

Algorithm 1 DASHA-PP

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*^(a), 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*^(a) nodes

7: **for** $i = 1, \dots, n$ in parallel **do**

8: **if** i^{th} node is *participating*^(a) **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: $m_i^{t+1} = \mathcal{C}_i \left(\frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right)$

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: $h_i^{t+1} = h_i^t$, $g_i^{t+1} = g_i^t$, $m_i^{t+1} = 0$

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.

Algorithm 2 Calculate k_i^{t+1} for **DASHA-PP** in the gradient setting. See line 9 in Alg. 1

1: $k_i^{t+1} = \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))$

Algorithm 3 Calculate k_i^{t+1} for **DASHA-PP-PAGE** in the finite-sum setting. See line 9 in Alg. 1

1: Generate a random set I_i^t of size B from $[m]$ with replacement

2: $k_i^{t+1} = \begin{cases} \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)), \\ \quad \text{with probability } p_{\text{page}} \text{ on all } \textit{participating} \text{ nodes,} \\ \frac{1}{B} \sum_{j \in I_i^t} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)), \\ \quad \text{with probability } 1 - p_{\text{page}} \text{ on all } \textit{participating} \text{ nodes} \end{cases}$

Algorithm 4 Calc. k_i^{t+1} for **DASHA-PP-FINITE-MVR** in the finite-sum setting. See line 9 in Alg. 1

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: $k_i^{t+1} = \frac{1}{m} \sum_{j=1}^m k_{ij}^{t+1}$

Algorithm 5 Calculate k_i^{t+1} for **DASHA-PP-MVR** in the stochastic setting. See line 9 in Alg. 1

1: Generate i.i.d. samples $\{\xi_{ij}^{t+1}\}_{j=1}^B$ of size B from \mathcal{D}_i .

2: $k_i^{t+1} = \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^{t+1}; \xi_{ij}^{t+1}) - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}) - b \left(h_i^t - \frac{1}{B} \sum_{j=1}^B \nabla f_i(x^t; \xi_{ij}^{t+1}) \right)$

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

$$\mathbb{E} \left[\|\nabla f(\hat{x}^T)\|^2 \right] \leq \frac{1}{T} \left[\frac{2\Delta_0}{\gamma} + \frac{2}{b} \|h^0 - \nabla f(x^0)\|^2 \right]$$

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

$$\begin{aligned} & + \left(\frac{32b\omega(2\omega+1)}{np_a^2} + \frac{4\left(1 - \frac{p_{aa}}{p_a}\right)}{np_a} \right) \left(\frac{1}{n} \sum_{i=1}^n \|h_i^0 - \nabla f_i(x^0)\|^2 \right) \\ & + \left(\frac{48b^2\omega(2\omega+1)}{p_a^2} + \frac{12b}{p_a} \right) \frac{\sigma^2}{nB}. \end{aligned}$$

In the next corollary, we choose momentum b and initialize vectors h_i^0 to get ε -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

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

communication rounds to get an ε -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.

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

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

and the expected number of stochastic gradient calculations

per node equals

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

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

7. The Problem of Estimating the Mean in the Partial Participation Setting

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

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

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

Next, we consider the same task in the partial participation setting with s -nice sampling, i.e., we sample a random set $S \subset [n]$ of $s \in [n]$ nodes without replacement and receive the mini-batches only from the sampled nodes. Such sampling of nodes satisfy Assumption 8 with $p_a = s/n$ and $p_a = s(s-1)/(n(n-1))$. In this case, the variance of the

estimator (See Lemma 1 with $r_i = 0$ and $s_i = \sum_{j \in I^i} x_{ij}$) is

$$\begin{aligned} & \mathbb{E}\left[\left\|\frac{1}{sB}\sum_{i \in S}\sum_{j \in I^i}x_{ij} - \frac{1}{nm}\sum_{i=1}^n\sum_{j=1}^m x_{ij}\right\|^2\right] \\ &= \frac{1}{sB}\frac{1}{nm}\sum_{i=1}^n\sum_{j=1}^m\left\|x_{ij} - \frac{1}{m}\sum_{j=1}^m x_{ij}\right\|^2 \\ & \quad \underbrace{\hspace{10em}}_{\mathcal{L}_{\max}^2} \\ & \quad + \frac{n-s}{s(n-1)}\frac{1}{n}\sum_{i=1}^n\left\|\frac{1}{m}\sum_{j=1}^m x_{ij} - \frac{1}{nm}\sum_{i=1}^n\sum_{j=1}^m x_{ij}\right\|^2 \\ & \quad \underbrace{\hspace{10em}}_{\widehat{\mathcal{L}}^2}. \end{aligned} \quad (12)$$

Let us assume that $s \leq n/2$. Note that (11) scales with any $B \geq 1$, while (12) only scales when $B = \mathcal{O}(\mathcal{L}_{\max}^2/\widehat{\mathcal{L}}^2)$. In other words, for large enough B , the variance in (12) does not significantly improves with the growth of B due to the term $\widehat{\mathcal{L}}^2$. 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.

References

- Alistarh, D., Grubic, D., Li, J., Tomioka, R., and Vojnovic, M. QSGD: Communication-efficient SGD via gradient quantization and encoding. In *Advances in Neural Information Processing Systems (NIPS)*, pp. 1709–1720, 2017.
- Arjevani, Y., Carmon, Y., Duchi, J. C., Foster, D. J., Srebro, N., and Woodworth, B. Lower bounds for non-convex stochastic optimization. *arXiv preprint arXiv:1912.02365*, 2019.
- Beznosikov, A., Horváth, S., Richtárik, P., and Safaryan, M. On biased compression for distributed learning. *arXiv preprint arXiv:2002.12410*, 2020.
- Carmon, Y., Duchi, J. C., Hinder, O., and Sidford, A. Lower bounds for finding stationary points i. *Mathematical Programming*, 184(1):71–120, 2020.
- Chang, C.-C. and Lin, C.-J. LIBSVM: a library for support vector machines. *ACM Transactions on Intelligent Systems and Technology (TIST)*, 2(3):1–27, 2011.
- Cutkosky, A. and Orabona, F. Momentum-based variance reduction in non-convex SGD. *arXiv preprint arXiv:1905.10018*, 2019.
- Fang, C., Li, C. J., Lin, Z., and Zhang, T. SPIDER: Near-optimal non-convex optimization via stochastic path in-

- egrated differential estimator. In *NeurIPS Information Processing Systems*, 2018.
- Goodfellow, I., Bengio, Y., Courville, A., and Bengio, Y. *Deep learning*, volume 1. MIT Press, 2016.
- Gorbunov, E., Burlachenko, K., Li, Z., and Richtárik, P. MARINA: Faster non-convex distributed learning with compression. In *38th International Conference on Machine Learning*, 2021.
- Horváth, S., Ho, C.-Y., Horvath, L., Sahu, A. N., Canini, M., and Richtárik, P. Natural compression for distributed deep learning. *arXiv preprint arXiv:1905.10988*, 2019a.
- Horváth, S., Kovalev, D., Mishchenko, K., Stich, S., and Richtárik, P. Stochastic distributed learning with gradient quantization and variance reduction. *arXiv preprint arXiv:1904.05115*, 2019b.
- Ioffe, S. and Szegedy, C. Batch normalization: Accelerating deep network training by reducing internal covariate shift. In *International Conference on Machine Learning*, pp. 448–456. PMLR, 2015.
- Kairouz, P., McMahan, H. B., Avent, B., Bellet, A., Bennis, M., Bhagoji, A. N., Bonawitz, K., Charles, Z., Cormode, G., Cummings, R., et al. Advances and open problems in federated learning. *Foundations and Trends® in Machine Learning*, 14(1–2):1–210, 2021.
- Karimireddy, S. P., Jaggi, M., Kale, S., Mohri, M., Reddi, S. J., Stich, S. U., and Suresh, A. T. Mime: Mimicking centralized stochastic algorithms in federated learning. *arXiv preprint arXiv:2008.03606*, 2020a.
- Karimireddy, S. P., Kale, S., Mohri, M., Reddi, S., Stich, S., and Suresh, A. T. Scaffold: Stochastic controlled averaging for federated learning. In *International Conference on Machine Learning*, pp. 5132–5143. PMLR, 2020b.
- Konečný, J., McMahan, H. B., Yu, F. X., Richtárik, P., Suresh, A. T., and Bacon, D. Federated learning: Strategies for improving communication efficiency. *arXiv preprint arXiv:1610.05492*, 2016.
- Li, T., Sahu, A. K., Zaheer, M., Sanjabi, M., Talwalkar, A., and Smith, V. Federated optimization in heterogeneous networks. *Proceedings of Machine Learning and Systems*, 2:429–450, 2020.
- Li, Z., Bao, H., Zhang, X., and Richtárik, P. PAGE: A simple and optimal probabilistic gradient estimator for nonconvex optimization. In *International Conference on Machine Learning*, pp. 6286–6295. PMLR, 2021a.
- Li, Z., Hanzely, S., and Richtárik, P. ZeroSARAH: Efficient nonconvex finite-sum optimization with zero full gradient computation. *arXiv preprint arXiv:2103.01447*, 2021b.
- Lin, Y., Han, S., Mao, H., Wang, Y., and Dally, W. J. Deep gradient compression: Reducing the communication bandwidth for distributed training. *arXiv preprint arXiv:1712.01887*, 2017.
- McMahan, B., Moore, E., Ramage, D., Hampson, S., and y Arcas, B. A. Communication-efficient learning of deep networks from decentralized data. In *Artificial intelligence and statistics*, pp. 1273–1282. PMLR, 2017.
- Mishchenko, K., Gorbunov, E., Takáč, M., and Richtárik, P. Distributed learning with compressed gradient differences. *arXiv preprint arXiv:1901.09269*, 2019.
- Narayanan, D., Harlap, A., Phanishayee, A., Seshadri, V., Devanur, N. R., Ganger, G. R., Gibbons, P. B., and Zaharia, M. PipeDream: generalized pipeline parallelism for dnn training. In *Proceedings of the 27th ACM Symposium on Operating Systems Principles*, pp. 1–15, 2019.
- Nesterov, Y. *Lectures on convex optimization*, volume 137. Springer, 2018.
- Nguyen, L., Liu, J., Scheinberg, K., and Takáč, M. SARAH: A novel method for machine learning problems using stochastic recursive gradient. In *The 34th International Conference on Machine Learning*, 2017.
- Paszke, A., Gross, S., Massa, F., Lerer, A., Bradbury, J., Chanan, G., Killeen, T., Lin, Z., Gimelshein, N., Antiga, L., et al. Pytorch: An imperative style, high-performance deep learning library. In *Advances in Neural Information Processing Systems (NeurIPS)*, 2019.
- Patel, K. K., Wang, L., Woodworth, B., Bullins, B., and Srebro, N. Towards optimal communication complexity in distributed non-convex optimization. In *Advances in Neural Information Processing Systems*, 2022.
- Ramaswamy, S., Mathews, R., Rao, K., and Beaufays, F. Federated learning for emoji prediction in a mobile keyboard. *arXiv preprint arXiv:1906.04329*, 2019.
- Ramesh, A., Pavlov, M., Goh, G., Gray, S., Voss, C., Radford, A., Chen, M., and Sutskever, I. Zero-shot text-to-image generation. *arXiv preprint arXiv:2102.12092*, 2021.
- Reddi, S., Charles, Z., Zaheer, M., Garrett, Z., Rush, K., Konečný, J., Kumar, S., and McMahan, H. B. Adaptive federated optimization. *arXiv preprint arXiv:2003.00295*, 2020.
- Richtárik, P., Sokolov, I., and Fatkhullin, I. EF21: A new, simpler, theoretically better, and practically faster error feedback. In *Neural Information Processing Systems, 2021.*, 2021.

- Richtárik, P., Sokolov, I., Fatkhullin, I., Gasanov, E., Li, Z., and Gorbunov, E. 3PC: Three point compressors for communication-efficient distributed training and a better theory for lazy aggregation. *arXiv preprint arXiv:2202.00998*, 2022.
- Sapio, A., Canini, M., Ho, C.-Y., Nelson, J., Kalnis, P., Kim, C., Krishnamurthy, A., Moshref, M., Ports, D. R., and Richtárik, P. Scaling distributed machine learning with in-network aggregation. *arXiv preprint arXiv:1903.06701*, 2019.
- Stich, S. U., Cordonnier, J.-B., and Jaggi, M. Sparsified SGD with memory. *Advances in Neural Information Processing Systems*, 31, 2018.
- Suresh, A. T., Sun, Z., Ro, J. H., and Yu, F. Correlated quantization for distributed mean estimation and optimization. *arXiv preprint arXiv:2203.04925*, 2022.
- Szlendak, R., Tyurin, A., and Richtárik, P. Permutation compressors for provably faster distributed nonconvex optimization. *arXiv preprint arXiv:2110.03300*, 2021.
- Tyurin, A. and Richtárik, P. DASHA: Distributed nonconvex optimization with communication compression and optimal oracle complexity. *International Conference on Learning Representations (ICLR)*, 2023.
- Vogels, T., He, L., Koloskova, A., Karimireddy, S. P., Lin, T., Stich, S. U., and Jaggi, M. RelaySum for decentralized deep learning on heterogeneous data. *Advances in Neural Information Processing Systems*, 34, 2021.
- Wangni, J., Wang, J., Liu, J., and Zhang, T. Gradient sparsification for communication-efficient distributed optimization. *Advances in Neural Information Processing Systems*, 31, 2018.
- Xu, H., Ho, C.-Y., Abdelmoniem, A. M., Dutta, A., Bergou, E. H., Karatsenidis, K., Canini, M., and Kalnis, P. Grace: A compressed communication framework for distributed machine learning. In *2021 IEEE 41st International Conference on Distributed Computing Systems (ICDCS)*, pp. 561–572. IEEE, 2021.
- Zhao, H., Burlachenko, K., Li, Z., and Richtárik, P. Faster rates for compressed federated learning with client-variance reduction. *arXiv preprint arXiv:2112.13097*, 2021a.
- Zhao, H., Li, Z., and Richtárik, P. FedPAGE: A fast local stochastic gradient method for communication-efficient federated learning. *arXiv preprint arXiv:2108.04755*, 2021b.

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A. Numerical Verification of Theoretical Dependencies

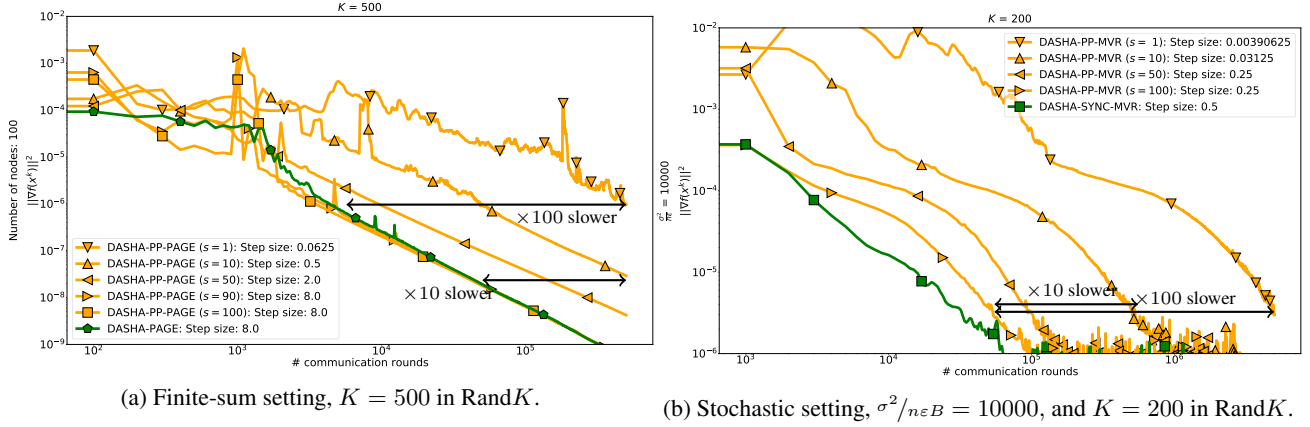


Figure 1: Classification task with the *real-sim* dataset.

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

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

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

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

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^{th} node, $y_{ij} \in \{1, 2\}$ is a corresponding label, m is the number of samples located on the i^{th} node, constant $\lambda = 0.001$ for all $i \in [n]$.

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

We use the standard setting in experiments⁵ where all parameters except step sizes are taken as suggested in theory. Step sizes are finetuned from a set $\{2^i \mid i \in [-10, 10]\}$. We emulate the partial participation setting using s -nice sampling with the number of nodes $n = 100$. We consider the RandK compressor and take the batch size $B = 1$. We plot the relation between communication rounds and values of the norm of gradients at each communication round.

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

B. Auxiliary facts

We list auxiliary facts that we use in our proofs:

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

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

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

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

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

B.1. Sampling Lemma

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

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

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

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

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

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 $i \in [n]$, nonrandom vector $r_i \in \mathbb{R}^d$ for all $i \in [n]$, and random vectors

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

then

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

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

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

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

Note, that

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

and

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

Using the law of total expectation and

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

we have

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

From the independence of random vectors s_i , we obtain

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

Using (15) and (16), we have

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

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

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

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

□

B.2. Compressors Facts

We define the $\text{Rand}K$ compressor that chooses without replacement K coordinates, scales them by a 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 $\text{Rand}K$ if

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

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

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

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

C. Proofs of Theorems

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

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

C.1. Standard Lemmas in the Nonconvex Setting

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

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 $\gamma > 0$, we have

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

Proof. Using L -smoothness, we have

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

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

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

□

Lemma 3. Suppose that Assumption 1 holds and

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

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

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

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

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

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

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 $\Psi^t \geq 0$ for all $t \in [T]$, to get the following inequality:

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

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

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

The lemma can be easily checked with the direct calculation.

C.2. Generic Lemmas

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

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

and

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

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

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

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

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

and

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

Thus, we can get

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

Due to the independence of compressors, we can use Lemma 1 with $r_i = g_i^t - h_i^t$ and $s_i = p_a \mathcal{C}_i \left(\frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right) - k_i^{t+1}$, and obtain

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

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

From Assumption 7, we have

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

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

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

□

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

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

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

Proof. Due to Lemma 2 and the update step from Line 5 in Algorithm 1, we have

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

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

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

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

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

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

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 $\left(\frac{\gamma a((2\omega+1)p_a - p_{aa})}{np_a^2} + \eta \left(\frac{a^2(2\omega+1-p_a)}{p_a} + (1-a)^2 \right) \right) \leq \eta$. Thus

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

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

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

□

C.3. Proof for DASHA-PP

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

1.

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

2.

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

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

3.

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

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

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

Using

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

and (14), we have

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

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

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

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

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

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

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 $\mathbb{E} [\|\nabla f(\hat{x}^T)\|^2] \leq \frac{2\Delta_0}{\gamma T}$.

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

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

After rearranging the terms, we get

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

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

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

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

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

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

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

and

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

Let us simplify the last inequality. First, note that

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

due to $b \leq p_a$. Second,

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

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

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

Using Lemma 4 and the assumption about γ , we get

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

It is left to apply Lemma 3 with

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

to conclude the proof. \square

C.4. Proof for DASHA-PP-PAGE

Let us denote

$$k_{i,1}^{t+1} := \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)),$$

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

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

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

Lemma 8. Suppose that Assumptions 3, 4, and 8 hold. For h_i^{t+1} and k_i^{t+1} from Algorithm 1 (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.

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

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

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

Using

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

$$\begin{aligned}
 &= p_a h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)) + (1 - p_a) h_i^t \\
 &= h_i^t + \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{page}}} (h_i^t - \nabla f_i(x^t)).
 \end{aligned}$$

and

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

we obtain

$$\begin{aligned}
 &\mathbb{E}_B \left[\mathbb{E}_{p_a} \left[\mathbb{E}_{p_{\text{page}}} [\|h^{t+1} - \nabla f(x^{t+1})\|^2] \right] \right] \\
 &\stackrel{(14)}{=} p_{\text{page}} \mathbb{E}_{p_a} [\|h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}]\|^2] + (1 - p_{\text{page}}) \mathbb{E}_B [\mathbb{E}_{p_a} [\|h_2^{t+1} - \mathbb{E}_B [\mathbb{E}_{p_a} [h_2^{t+1}]]\|^2]] \\
 &\quad + p_{\text{page}} \|\mathbb{E}_{p_a} [h_1^{t+1}] - \nabla f(x^{t+1})\|^2 + (1 - p_{\text{page}}) \|\mathbb{E}_B [\mathbb{E}_{p_a} [h_2^{t+1}]] - \nabla f(x^{t+1})\|^2 \\
 &= p_{\text{page}} \mathbb{E}_{p_a} [\|h_1^{t+1} - \mathbb{E}_{p_a} [h_1^{t+1}]\|^2] + (1 - p_{\text{page}}) \mathbb{E}_B [\mathbb{E}_{p_a} [\|h_2^{t+1} - \mathbb{E}_B [\mathbb{E}_{p_a} [h_2^{t+1}]]\|^2]] \\
 &\quad + \left(p_{\text{page}} \left(1 - \frac{b}{p_{\text{page}}} \right)^2 + (1 - p_{\text{page}}) \right) \|h^t - \nabla f(x^t)\|^2. \tag{22}
 \end{aligned}$$

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

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

From Assumption 3, we have

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

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

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

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

Next, we use Assumptions 3 and 4 to get

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

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

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

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

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

Let us consider $E_B \left[E_{p_a} \left[\|h_{i,1}^{t+1} - E_B [E_{p_a} [h_{i,1}^{t+1}]]\|^2 \right] \right]$:

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

Considering (13) and Assumption 3, we obtain

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

Next, we obtain the bound for $E_B \left[E_{p_a} \left[\|h_{i,2}^{t+1} - E_B [E_{p_a} [h_{i,2}^{t+1}]]\|^2 \right] \right]$:

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

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

$$\begin{aligned}
 & E_B \left[E_{p_a} \left[E_{p_{\text{page}}} \left[\|h_i^{t+1} - \nabla f_i(x^{t+1})\|^2 \right] \right] \right] \\
 &\leq p_{\text{page}} \left(\frac{2(1 - p_a) L_i^2}{p_a} \|x^{t+1} - x^t\|^2 + \frac{2(1 - p_a) b^2}{p_a p_{\text{page}}^2} \|h_i^t - \nabla f_i(x^t)\|^2 \right)
 \end{aligned}$$

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

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[\|h_i^{t+1} - \nabla f_i(x^{t+1})\|^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] \\
 & + \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}}}{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] \\
 & + \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 \\
 & + \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 \\
 & + \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 \\
 & + \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}$$

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

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

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

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

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

It is left to consider Assumptions 3 and 4 to get

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

□

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

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

$$+ \frac{16}{np_a^2 p_{\text{page}}} \left(\left(1 - \frac{p_{\text{aa}}}{p_a} \right) \widehat{L}^2 + \frac{(1 - p_{\text{page}}) L_{\max}^2}{B} \right)^{1/2} \Big)^{-1}$$

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

Proof. Let us fix constants $\nu, \rho \in [0, \infty)$ that we will define later. Considering Lemma 6, Lemma 8, 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] \\ & + \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_{\text{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] \\ & + \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] \\ & + \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}}} [\|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[\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} [\|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] \\ & + \frac{4\gamma\omega(2\omega + 1)}{np_a^2} \mathbb{E} \left[\left(2\widehat{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_{\text{aa}}) \widehat{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_{\text{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) \widehat{L}^2}{p_a} + \frac{(1 - p_{\text{page}}) L_{\max}^2}{p_a B} \right) \|x^{t+1} - x^t\|^2 \right. \end{aligned}$$

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

After rearranging the terms, we get

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

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 $\nu = \frac{\gamma}{b}$, then

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

therefore

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

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

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

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

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

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

therefore

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

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

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

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

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

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

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

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

Using Lemma 4 and the assumption about γ , we get

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

It is left to apply Lemma 3 with

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

to conclude the proof. \square

Corollary 1. Let the assumptions from Theorem 3 hold and $p_{\text{page}} = B/(m+B)$. 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 ε -solution and the expected number of gradient calculations per node equals $\mathcal{O}(m + BT)$.

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

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

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

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

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

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

Proof. The communication complexity equals

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

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

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

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

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

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

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

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

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

□

C.5. Proof for DASHA-PP-FINITE-MVR

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 (DASHA-PP-FINITE-MVR) we have

1.

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

2.

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

3.

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

4.

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

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

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

thus

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

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

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

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

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

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

Due to Assumptions 3 and 4, we have

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

Let us get the bound for the second inequality:

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

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

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

$$\begin{aligned}
 & + \frac{2b^2}{p_a B m} \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + \left(\frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\
 & \leq \left(\frac{2L_{\max}^2}{p_a B} + \frac{2(1-p_a)L_i^2}{p_a} \right) \|x^{t+1} - x^t\|^2 \\
 & + \frac{2b^2}{p_a B m} \sum_{j=1}^m \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 + \left(\frac{2(1-p_a)b^2}{p_a} + (1-b)^2 \right) \|h_i^t - \nabla f_i(x^t)\|^2,
 \end{aligned}$$

where we used Assumptions 3 and 4. We continue the proof by considering $\mathbb{E}_B \left[\mathbb{E}_{p_a} \left[\|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \right]$:

$$\begin{aligned}
 & \mathbb{E}_B \left[\mathbb{E}_{p_a} \left[\|h_{ij}^{t+1} - \nabla f_{ij}(x^{t+1})\|^2 \right] \right] \\
 & \stackrel{(14)}{=} \mathbb{E}_B \left[\mathbb{E}_{p_a} \left[\left\| h_{ij}^{t+1} - (\nabla f_{ij}(x^{t+1}) + (1-b)(h_{ij}^t - \nabla f_{ij}(x^t))) \right\|^2 \right] \right] \\
 & + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
 & = \frac{p_a B}{m} \mathbb{E}_B \left[\left\| h_{ij}^t + \frac{m}{B p_a} (\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))) - (\nabla f_{ij}(x^{t+1}) + (1-b)(h_{ij}^t - \nabla f_{ij}(x^t))) \right\|^2 \right] \\
 & + \left(1 - \frac{p_a B}{m} \right) \|h_{ij}^t - (\nabla f_{ij}(x^{t+1}) + (1-b)(h_{ij}^t - \nabla f_{ij}(x^t)))\|^2 \\
 & + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
 & = \frac{\left(1 - \frac{p_a B}{m} \right)^2}{\frac{p_a B}{m}} \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
 & + \left(1 - \frac{p_a B}{m} \right) \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
 & + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
 & = \frac{\left(1 - \frac{p_a B}{m} \right)}{\frac{p_a B}{m}} \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t) - b(h_{ij}^t - \nabla f_{ij}(x^t))\|^2 \\
 & + (1-b)^2 \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2 \\
 & \stackrel{(13)}{\leq} \frac{2 \left(1 - \frac{p_a B}{m} \right)}{\frac{p_a B}{m}} \|\nabla f_{ij}(x^{t+1}) - \nabla f_{ij}(x^t)\|^2 + \left(\frac{2 \left(1 - \frac{p_a B}{m} \right) b^2}{\frac{p_a B}{m}} + (1-b)^2 \right) \|h_{ij}^t - \nabla f_{ij}(x^t)\|^2.
 \end{aligned}$$

It is left to consider Assumption 4:

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

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

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

$$+ \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2.$$

Using Lemma 1, we get

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

where we used Assumptions 3 and 4. \square

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

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

$g_i^0 = h_i^0 = \nabla f_i(x^0)$ 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 (DASHA-PP-FINITE-MVR) then $\mathbb{E} \left[\|\nabla f(\widehat{x}^T)\|^2 \right] \leq \frac{2\Delta_0}{\gamma T}$.

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

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

$$\begin{aligned}
 & + \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] \\
 & + \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} \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] \\
 & + \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] \\
 & + \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

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

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] \\ & + \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 + (1 - b) \frac{1}{n} \sum_{i=1}^n \|h_i^t - \nabla f_i(x^t)\|^2 \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}$$

After rearranging the terms, we get

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

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

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

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

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

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

therefore

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

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

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

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

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

and

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

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

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

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

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

$$\frac{4\gamma\omega(2\omega+1)}{np_a^2} \left(\frac{2L_{\max}^2}{B} + 2\hat{L}^2 \right)$$

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

All in all, we have

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

Using Lemma 4 and the assumption about γ , we get

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

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

It is left to apply Lemma 3 with

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

to conclude the proof. \square

C.6. Proof for DASHA-PP-MVR

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

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

1.

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

2.

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

3.

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

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

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

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

Using

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

and (14), we have

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

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] \\ & \quad + \frac{2}{n^2 p_a} \sum_{i=1}^n \mathbb{E}_k \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)))\|^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 \\ &= \frac{2b^2}{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+1})\|^2 \right] \\ & \quad + \frac{2(1-b)^2}{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}) - (\nabla f_i(x^{t+1}) - \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. \\ &= \frac{2b^2}{n^2 p_a B^2} \sum_{i=1}^n \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] \\ & \quad + \frac{2(1-b)^2}{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}) - (\nabla f_i(x^{t+1}) - \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 \end{aligned}$$

$$+ (1-b)^2 \|h^t - \nabla f(x^t)\|^2.$$

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

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

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

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

Now, we prove the second inequality:

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

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

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

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

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

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

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

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

$$\begin{aligned}
 & \mathbb{E}_k \left[\|k_i^{t+1}\|^2 \right] \\
 & = \mathbb{E}_k \left[\|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - b(h_i^t - \nabla f_i(x^t; \xi_i^{t+1}))\|^2 \right] \\
 & \stackrel{(14)}{=} \mathbb{E}_k \left[\|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - b(h_i^t - \nabla f_i(x^t; \xi_i^{t+1})) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t)))\|^2 \right] \\
 & + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
 & = \mathbb{E}_k \left[\|b(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1})) + (1-b)(\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t)))\|^2 \right] \\
 & + \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t) - b(h_i^t - \nabla f_i(x^t))\|^2 \\
 & \stackrel{(13)}{\leq} 2b^2 \mathbb{E}_k \left[\|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^{t+1})\|^2 \right] \\
 & + 2(1-b)^2 \mathbb{E}_k \left[\|\nabla f_i(x^{t+1}; \xi_i^{t+1}) - \nabla f_i(x^t; \xi_i^{t+1}) - (\nabla f_i(x^{t+1}) - \nabla f_i(x^t))\|^2 \right] \\
 & + 2 \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^2 + 2b^2 \|h_i^t - \nabla f_i(x^t)\|^2.
 \end{aligned}$$

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

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

□

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

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

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

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

Proof. Let us fix constants $\nu, \rho \in [0, \infty)$ that we will define later. Considering Lemma 6, Lemma 10, 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} \left[\left\| g^{t+1} - h^{t+1} \right\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| g_i^{t+1} - h_i^{t+1} \right\|^2 \right] \\ &\quad + \nu \mathbb{E} \left[\left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] + \rho \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \\ &\leq \mathbb{E} \left[f(x^t) - \frac{\gamma}{2} \left\| \nabla f(x^t) \right\|^2 - \left(\frac{1}{2\gamma} - \frac{L}{2} \right) \left\| x^{t+1} - x^t \right\|^2 + \gamma \left\| h^t - \nabla f(x^t) \right\|^2 \right] \\ &\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[\left\| g^t - h^t \right\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| g_i^t - h_i^t \right\|^2 \right] \\ &\quad + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| k_i^{t+1} \right\|^2 \right] \\ &\quad + \nu \mathbb{E} \left[\left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] + \rho \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \\ &= \mathbb{E} \left[f(x^t) - \frac{\gamma}{2} \left\| \nabla f(x^t) \right\|^2 - \left(\frac{1}{2\gamma} - \frac{L}{2} \right) \left\| x^{t+1} - x^t \right\|^2 + \gamma \left\| h^t - \nabla f(x^t) \right\|^2 \right] \\ &\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[\left\| g^t - h^t \right\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| g_i^t - h_i^t \right\|^2 \right] \\ &\quad + \frac{4\gamma\omega(2\omega+1)}{np_a^2} \mathbb{E} \left[\mathbb{E}_k \left[\frac{1}{n} \sum_{i=1}^n \left\| k_i^{t+1} \right\|^2 \right] \right] \\ &\quad + \nu \mathbb{E} \left[\mathbb{E}_B \left[\mathbb{E}_{p_a} \left[\left\| h^{t+1} - \nabla f(x^{t+1}) \right\|^2 \right] \right] \right] \\ &\quad + \rho \mathbb{E} \left[\mathbb{E}_B \left[\mathbb{E}_{p_a} \left[\frac{1}{n} \sum_{i=1}^n \left\| h_i^{t+1} - \nabla f_i(x^{t+1}) \right\|^2 \right] \right] \right] \\ &\leq \mathbb{E} \left[f(x^t) - \frac{\gamma}{2} \left\| \nabla f(x^t) \right\|^2 - \left(\frac{1}{2\gamma} - \frac{L}{2} \right) \left\| x^{t+1} - x^t \right\|^2 + \gamma \left\| h^t - \nabla f(x^t) \right\|^2 \right] \\ &\quad + \frac{\gamma(2\omega+1)}{p_a} \mathbb{E} \left[\left\| g^t - h^t \right\|^2 \right] + \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2} \mathbb{E} \left[\frac{1}{n} \sum_{i=1}^n \left\| g_i^t - h_i^t \right\|^2 \right] \\ &\quad + \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) \left\| x^{t+1} - x^t \right\|^2 + 2b^2 \frac{1}{n} \sum_{i=1}^n \left\| h_i^t - \nabla f_i(x^t) \right\|^2 \right] \\ &\quad + \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) \left\| x^{t+1} - x^t \right\|^2 \right) \end{aligned}$$

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

After rearranging the terms, we get

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

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

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

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

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

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

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

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

and

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

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

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

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

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] \\
 & + \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{12\gamma\omega(2\omega+1)}{np_a^2} \left(\frac{2(1-b)^2 L_\sigma^2}{B} + 2\widehat{L}^2 \right) \right. \\
 & \quad \left. - \frac{3\gamma}{np_a b} \left(\frac{2(1-b)^2 L_\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] \\
 & + \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} \\
 & = \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{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}$$

Also, we can simplify the last term:

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

$$\leq \frac{16b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{4b\gamma}{np_a},$$

thus

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

Using Lemma 4 and the assumption about γ , we get

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

It is left to apply Lemma 3 with

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

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

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

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

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

Proof. Using the result from Theorem 4, we have

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

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 $\frac{1}{b} = \Theta\left(\max\left\{\frac{\omega}{p_a}\sqrt{\frac{\sigma^2}{n\varepsilon B}}, \frac{\sigma^2}{p_a n \varepsilon B}\right\}\right) \leq \Theta\left(\max\left\{\frac{\omega^2}{p_a}, \frac{\sigma^2}{p_a n \varepsilon B}\right\}\right)$, thus

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

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

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

Let us bound the norms:

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

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

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

Using the choice of B_{init} and b , we obtain

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

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

Corollary 4. Suppose that assumptions of Corollary 3 hold, batch size $B \leq \min \left\{ \frac{\sigma}{p_a \sqrt{\varepsilon n}}, \frac{L_\sigma^2}{\mathbb{1}_{p_a}^2 L^2} \right\}$, we take RandK

compressors with $K = \Theta\left(\frac{Bd\sqrt{\varepsilon n}}{\sigma}\right)$. Then the communication complexity equals

$$\mathcal{O}\left(\frac{d\sigma}{\sqrt{p_a}\sqrt{n\varepsilon}} + \frac{L_\sigma\Delta_0d}{p_a\sqrt{n\varepsilon}}\right), \quad (9)$$

and the expected number of stochastic gradient calculations per node equals

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

Proof. The communication complexity equals

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

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

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

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 complexity equals

$$\begin{aligned} \mathcal{O}(d + KT) &= \mathcal{O}\left(d + \frac{\Delta_0}{\varepsilon} \left[\frac{d}{p_a\sqrt{n}} L + \frac{d}{p_a\sqrt{n}} \left(\hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{d}{p_a\sqrt{n}} L_\sigma \right] + \frac{d\sigma}{\sqrt{p_a}\sqrt{n\varepsilon}} \right) \\ &= \mathcal{O}\left(\frac{d\sigma}{\sqrt{p_a}\sqrt{n\varepsilon}} + \frac{L_\sigma\Delta_0d}{p_a\sqrt{n\varepsilon}}\right) \end{aligned}$$

And the expected number of stochastic gradient calculations per node equals

$$\begin{aligned} &\mathcal{O}(B_{\text{init}} + BT) \\ &= \mathcal{O}\left(\frac{\sigma^2}{\sqrt{p_a}n\varepsilon} + \frac{B\omega}{\sqrt{p_a}}\sqrt{\frac{\sigma^2}{n\varepsilon B}} + \frac{\Delta_0}{\varepsilon} \left[BL + B \frac{\omega}{p_a\sqrt{n}} \left(\hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + B \sqrt{\frac{\sigma^2}{p_a^2\varepsilon n^2 B}} \left(\mathbb{1}_{p_a} \hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) \right] + B \frac{\sigma^2}{\sqrt{p_a}n\varepsilon B} \right) \\ &= \mathcal{O}\left(\frac{\sigma^2}{\sqrt{p_a}n\varepsilon} + \frac{Bd}{K\sqrt{p_a}}\sqrt{\frac{\sigma^2}{n\varepsilon B}} + \frac{\Delta_0}{\varepsilon} \left[BL + B \frac{d}{Kp_a\sqrt{n}} \left(\hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + B \sqrt{\frac{\sigma^2}{p_a^2\varepsilon n^2 B}} \frac{L_\sigma}{\sqrt{B}} \right] + \frac{\sigma^2}{\sqrt{p_a}n\varepsilon} \right) \\ &= \mathcal{O}\left(\frac{\sigma^2}{\sqrt{p_a}n\varepsilon} + \frac{\sigma^2}{\sqrt{p_a}n\varepsilon\sqrt{B}} + \frac{\Delta_0}{\varepsilon} \left[\frac{\sigma}{p_a\sqrt{\varepsilon n}} L + \frac{\sigma}{p_a\sqrt{\varepsilon n}} \left(\hat{L} + \frac{L_\sigma}{\sqrt{B}} \right) + \frac{\sigma}{p_a\sqrt{\varepsilon n}} L_\sigma \right] \right) \\ &= \mathcal{O}\left(\frac{\sigma^2}{\sqrt{p_a}n\varepsilon} + \frac{L_\sigma\Delta_0\sigma}{p_a\varepsilon^{3/2}n}\right). \end{aligned}$$

□

D. 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 ε -solution, if $\mathbb{E}[f(\hat{x})] - f^* \leq \varepsilon$.

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

D.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 ε -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 & 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 ε -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.

D.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 ε -solution DASHA-PP have to run

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

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

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

communication rounds to get ε -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.

D.3. Stochastic Setting

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

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

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

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

The provided theorems states that to get ε -solution DASHA-PP have to run

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

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

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

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

communication rounds to get ε -solution⁷.

In the stochastic setting, the comparison is a little bit more complicated. As in the finite-sum setting, 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). However, DASHA-PP-MVR has also suboptimal term \mathcal{P}_2 . This suboptimality is tightly connected with the suboptimality of B_{init} in the general nonconvex case, which we discuss in Section 6.3, and it also appears in the analysis of DASHA-MVR (Tyurin & Richtárik, 2023). Let us provide the counterpart of Corollary 4. The corollary reveals that we can escape regimes when \mathcal{P}_2 is the bottleneck by choosing the parameters of the compressors.

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

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

and the expected number of stochastic gradient calculations per node equals

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

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

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

D.4. Proofs of Theorems

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

D.4.1. STANDARD LEMMA UNDER POLYAK-ŁOJASIEWICZ CONDITION

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

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

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

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

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

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

Unrolling the inequality, we have

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

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

D.4.2. GENERIC LEMMA

We now provide the counterpart of Lemma 6.

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

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

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

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

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

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

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

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 $\eta = \frac{4\gamma((2\omega+1)p_a - p_{aa})}{np_a^2}$, 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

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

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

D.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 $a = \frac{p_a}{2\omega+1}$, $b = \frac{p_a}{2-p_a}$,

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

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

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

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

After rearranging the terms, we get

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

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

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

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

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

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

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

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

and

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

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

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

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

Using Lemma 4 and the assumption about γ , we get

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

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

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

In the view of Lemma 11 with

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

we can conclude the proof of the theorem. \square

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

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

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

Proof. Let us fix constants $\nu, \rho \in [0, \infty)$ that we will define later. Considering Lemma 12, Lemma 8, 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\widehat{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})\widehat{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)\widehat{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}$$

After rearranging the terms, we get

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

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

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

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

therefore

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

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

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

therefore

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

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

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

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

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

Combining all bounds together, we obtain the following inequality:

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

Using Lemma 4 and the assumption about γ , we get

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

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

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

It is left to apply Lemma 11 with

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

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

to conclude the proof. \square

D.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 $a = \frac{p_a}{2\omega+1}$, $b \in \left(0, \frac{p_a}{2-p_a}\right]$,

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

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

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

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

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

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

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

After rearranging the terms, we get

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

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

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

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

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

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

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

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

and

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

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

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

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_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 + \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_a b} \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]
 \end{aligned}$$

$$+ \left(\frac{20b^2\gamma\omega(2\omega+1)}{np_a^2} + \frac{4\gamma b}{np_a} + \left(\frac{40b\gamma\omega(2\omega+1)}{np_a^2} + \frac{8\gamma(p_a - p_{aa})}{np_a^2} \right) \frac{2b^2}{p_a} \right) \frac{\sigma^2}{B}.$$

Also, we can simplify the last term:

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

thus

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

Using Lemma 4 and the assumption about γ , we get

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

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

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

It is left to apply Lemma 11 with

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

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

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

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

and the expected number of stochastic gradient calculations per node equals

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

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

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

communication rounds in the stochastic settings to get ε -solution. Note that $K = \mathcal{O} \left(\frac{d}{p_a \sqrt{n}} \right)$. Moreover, 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. Considering Theorem 6, the communication complexity equals

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

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

The expected number of stochastic gradient calculations per node equals

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

□

E. Description of DASHA-PP-SYNC-MVR

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

Algorithm 6 DASHA-PP-SYNC-MVR

```

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:         $m_i^{t+1} = \mathcal{C}_i \left( \frac{1}{p_a} k_i^{t+1} - \frac{a}{p_a} (g_i^t - h_i^t) \right)$ 
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.

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 $B' \geq B \geq 1$

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

and $h_i^0 = g_i^0$ for all $i \in [n]$ in Algorithm 6. Then

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

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

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 $\|x\|_0$ is the number of nonzero components of $x \in \mathbb{R}^d$. Let $\zeta_{\mathcal{C}} = \max_{i \in [n]} \zeta_{\mathcal{C}_i}$.

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

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

Corollary 6. Suppose that assumptions from Theorem 11 hold, probability $p_{\text{mega}} = \min \left\{ \frac{\zeta_{\mathcal{C}}}{d}, \frac{n\epsilon B}{\sigma^2} \right\}$, batch size $B' = \Theta \left(\frac{\sigma^2}{n\epsilon} \right)$, 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 $B_{\text{init}} = \Theta \left(\frac{B}{p_{\text{mega}} \sqrt{p_a}} \right) = \Theta \left(\max \left\{ \frac{Bd}{\sqrt{p_a} \zeta_{\mathcal{C}}}, \frac{\sigma^2}{\sqrt{p_a} n \epsilon} \right\} \right)$, then DASHA-PP-SYNC-MVR needs

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

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

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

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 $B' \geq B \geq 1$,

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

and $h_i^0 = g_i^0$ for all $i \in [n]$ in Algorithm 6. Then

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

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 $p_{\text{mega}} = \min \left\{ \frac{\zeta_{\mathcal{C}}}{d}, \frac{\mu n \epsilon B}{\sigma^2} \right\}$, batch size $B' = \Theta \left(\frac{\sigma^2}{\mu n \epsilon} \right)$ then DASHA-PP-SYNC-MVR needs

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

communication rounds to get an ε -solution, the expected communication complexity is equal to $\tilde{O}(\zeta_c T)$, and the expected number of stochastic gradient calculations per node equals $\tilde{O}(BT)$, where ζ_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

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

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 6: the first one from random samples ξ_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. ξ_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.

Lemma 13. Suppose that Assumptions 3, 5, 7 and 8 hold and let us consider sequences $\{g_i^{t+1}\}_{i=1}^n$ and $\{h_i^{t+1}\}_{i=1}^n$ from Algorithm 6, then

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

and

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

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

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

Using

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

and

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

we have

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

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

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

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

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

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

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

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

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

□

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

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

and

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

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

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

and

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

we have

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

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 obtain

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

Let us consider $\mathbb{E}_k \left[\|k_{i,1}^{t+1} - \mathbb{E}_k \left[k_{i,1}^{t+1} \right]\|^2 \right]$.

$$\mathbb{E}_k \left[\|k_{i,1}^{t+1} - \mathbb{E}_k \left[k_{i,1}^{t+1} \right]\|^2 \right]$$

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

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

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

Due to Assumptions 5 and 6, we have

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

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

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

Due to Assumptions 6, we have

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

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

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

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

Using Assumption 3, we get

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

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 [\mathbb{E}_{p_a} [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 [\mathbb{E}_{p_a} [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) \|\nabla f_i(x^{t+1}) - \nabla f_i(x^t)\|^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
 \end{aligned}$$

$$\begin{aligned}
 & \stackrel{(14)}{=} \frac{p_{\text{mega}}}{p_a} \mathbb{E}_k \left[\|k_{i,1}^{t+1} - \mathbb{E}_k[k_{i,1}^{t+1}]\|^2 \right] \\
 & + \frac{(1-p_{\text{mega}})}{p_a} \mathbb{E}_k \left[\|k_{i,2}^{t+1} - \mathbb{E}_k[k_{i,2}^{t+1}]\|^2 \right] \\
 & + \frac{p_{\text{mega}}(1-p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) - \frac{b}{p_{\text{mega}}} (h_i^t - \nabla f_i(x^t)) \right\|^2 \\
 & + \frac{(1-p_{\text{mega}})(1-p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\
 & + \left(p_{\text{mega}} \left(1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1-p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2 \\
 & \stackrel{(13)}{\leq} \frac{p_{\text{mega}}}{p_a} \mathbb{E}_k \left[\|k_{i,1}^{t+1} - \mathbb{E}_k[k_{i,1}^{t+1}]\|^2 \right] \\
 & + \frac{(1-p_{\text{mega}})}{p_a} \mathbb{E}_k \left[\|k_{i,2}^{t+1} - \mathbb{E}_k[k_{i,2}^{t+1}]\|^2 \right] \\
 & + \frac{2(1-p_a)}{p_a} \left\| \nabla f_i(x^{t+1}) - \nabla f_i(x^t) \right\|^2 \\
 & + \frac{2(1-p_a)b^2}{p_{\text{mega}}p_a} \|h_i^t - \nabla f_i(x^t)\|^2 + \left(p_{\text{mega}} \left(1 - \frac{b}{p_{\text{mega}}} \right)^2 + (1-p_{\text{mega}}) \right) \|h_i^t - \nabla f_i(x^t)\|^2.
 \end{aligned}$$

Using (34) and (35), we get

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

Next, due to Assumption 3, we obtain

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

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

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

□

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 $B' \geq B \geq 1$

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

and $h_i^0 = g_i^0$ for all $i \in [n]$ in Algorithm 6. Then

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

Proof. Due to Lemma 2 and the update step from Line 5 in Algorithm 6, we have

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

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

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

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

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 $1 - p_{\text{mega}} \leq 1$,

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

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

and

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

Thus

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

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

After rearranging the terms, we get

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

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

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

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

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 $\eta = \frac{\gamma((2\omega+1)p_a - p_{aa})}{np_a^2}$, 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} \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] \\
 & - \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} \left[\|x^{t+1} - 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] \\
 & + (\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'} \\
 & \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{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} \left[\|x^{t+1} - 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] \\
 & + (\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]
 \end{aligned}$$

$$+ \left(\frac{2\nu b^2}{np_{\text{mega}}p_a} + \frac{2\rho b^2}{p_a p_{\text{mega}}} \right) \frac{\sigma^2}{B'},$$

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

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

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

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

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} + \widehat{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})\widehat{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)\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'} \\
 & \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} + \widehat{L}^2 \right) - \left(\frac{8\gamma L_\sigma^2}{np_{\text{mega}} p_a^2 B} + \frac{8\gamma(1 - \frac{p_{aa}}{p_a})\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}$$

Using Lemma 4 and the assumption about γ , we get

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

It is left to apply Lemma 3 with

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

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

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

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

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

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

Using

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

and

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

we have

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

$$\left. \begin{aligned} & + \frac{8\sigma^2}{np_{\text{mega}}p_a B_{\text{init}}} \right] \\ & + \frac{2\varepsilon}{3}. \end{aligned}$$

Therefore, we can take the following T to get ε -solution.

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

Considering the choice of p_{mega} and B_{init} , we obtain

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

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

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

and $h_i^0 = g_i^0$ for all $i \in [n]$ in Algorithm 6. Then

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

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

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

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

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

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

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 $\eta = \frac{2\gamma((2\omega+1)p_a - p_{aa})}{np_a^2}$, we guarantee

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

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

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

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

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

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

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

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

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} [\|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(\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} [\|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'} \\
 & \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(1 - \frac{p_{aa}}{p_a})\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}$$

Using Lemma 4 and the assumption about γ , we get

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

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

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

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

It is left to apply Lemma 11 with

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

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