OPENFABRICS ALLIANCE

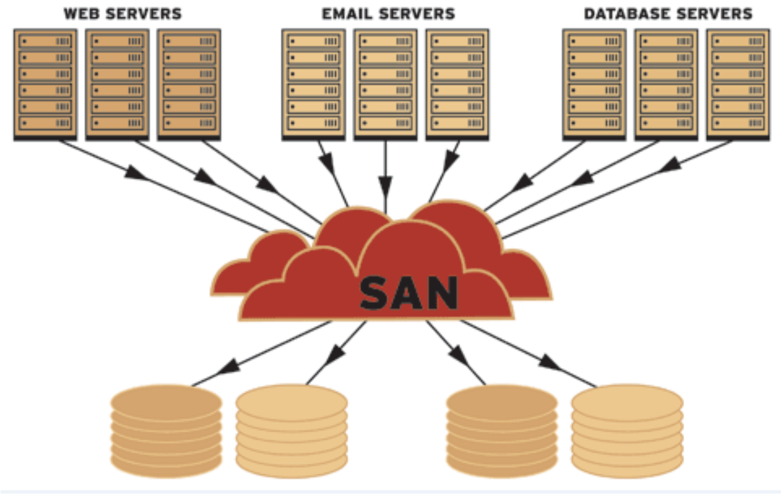
10TH ANNUAL INTERNATIONAL DEVELOPER WORKSHOP

OFVWG: Erasure Coding RDMA Offload

Sagi Grimberg

Problem Statement

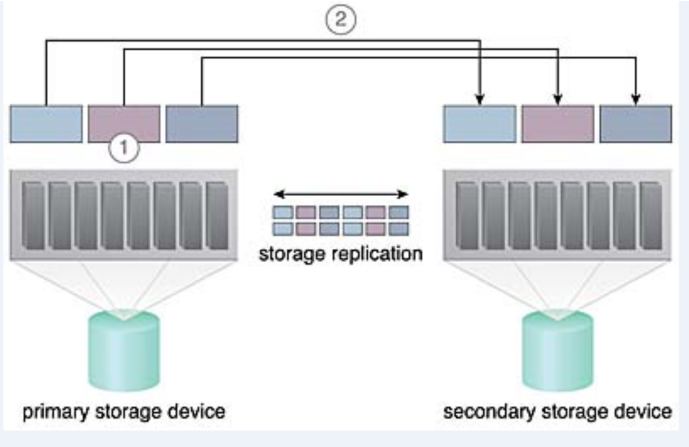
- Modern storage arrays are usually distributed in a clustered environment.



- Problem: Disks and/or nodes inevitably tend to fail.
  – How can we survive failures and keep our data intact?

RAID 1 (Replication)

- Instead of storing the data once, we will store more copies of the data on another disk/node.



- If a disk/node fail, we are able to still recover the data.
- If we want to survive X failures, we need to replicate X instances of the data.

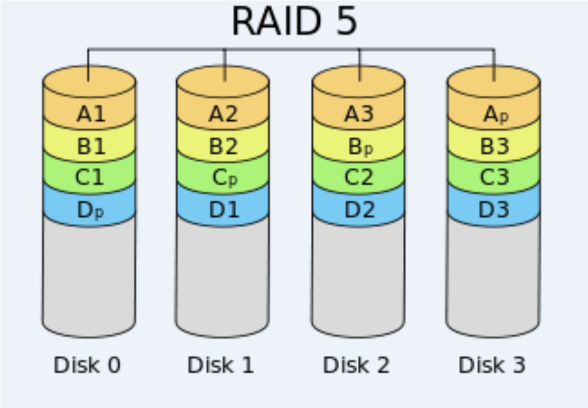
RAID 1 pros/cons

- Pros:
  - Simple to do
  - No need for extra computation
  - No need for reconstruct logic

- Cons:
  - Requires a high storage space for redundancy
  - Inefficient wire utilization

RAID 5 (single parity block)

- We divide our data into X blocks and calculate a single parity block and store it as well.



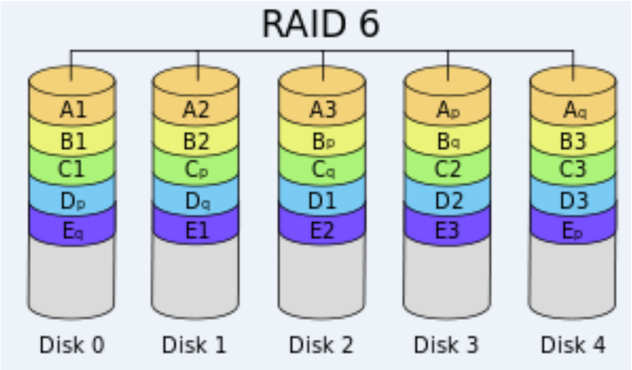
- If any of the drives fail we can reconstruct the original data back from the parity block.

RAID 5 pros/cons

- Pros:
  - Efficient storage utilization (small storage space for redundancy)
  - Efficient wire utilization
- Cons:
  - Requires computation to generate the parity block
  - Requires computation to reconstruct the original data
  - Need multi-level RAID to survive more than a single failure.

RAID 6 (dual parity block)

- We divide our data into X blocks and calculate two parity block and store them as well.



- If any two drives/nodes fail we can reconstruct the original data back from the parity blocks.

RAID 6 pros/cons

- Pros:
  - Efficient storage utilization (small storage space for redundancy)
  - Efficient wire utilization
- Cons:
  - Requires computation to generate two parity blocks
  - Requires computation to reconstruct the original data
  - Need multi-level RAID to survive more than two failures.

Erasure coding (generalize RAID)

- There are different types of erasure codes (Reed-Solomon, Cauchy and other MDS codes).
- The mathematical approach is to use higher rank polynomials over Galois finite fields GF(2^w) in order to use minimum storage for K number of disk/node failures.
- Codes can be systematic (raw data is stored) or non-systematic (data projections are stored).

Erasure coding (generalize RAID)

- Erasure codes allows us to survive M failures for any K data blocks where: $K+M \leq 2 \uparrow w$

- For example if we use $GF(2 \uparrow 4)$ and we want to survive 4 disk failures we can protect 12 data blocks.
  - This means we only spend 33.3% of storage to store redundancy metadata.

Erasure coding Illustration

Reed Solomon Systematic Matrix Encoding Process

$$
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 \\
g_0 & g_1 & g_2 & g_3 & g_4 \\
g_5 & g_6 & g_7 & g_8 & g_9
\end{bmatrix}
\begin{bmatrix}
d_0 \\ d_1 \\ d_2 \\ d_3 \\ d_4
\end{bmatrix}
=
\begin{bmatrix}
d_0 \\ d_1 \\ d_2 \\ d_3 \\ d_4 \\ P_1 \\ P_2 \\ P_3
\end{bmatrix}
$$

Generator Matrix　　data　　code word

Erasure coding Decode Illustration

Reed Solomon Systematic Matrix Decoding Process

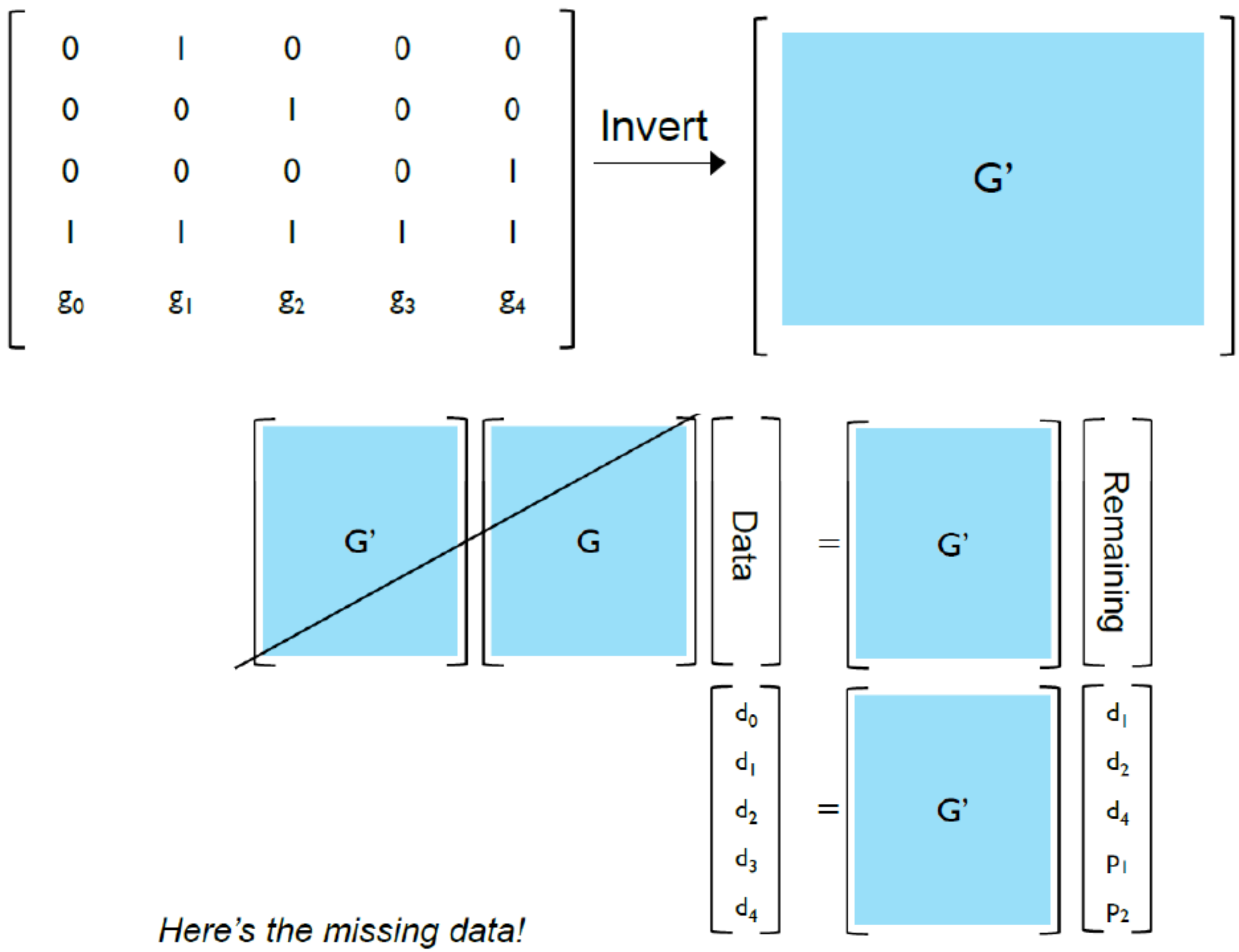
$$
\begin{bmatrix}
\cancel{1} & \cancel{0} & \cancel{0} & \cancel{0} & \cancel{0} \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
\cancel{0} & \cancel{0} & \cancel{0} & \cancel{1} & \cancel{0} \\
0 & 0 & 0 & 0 & 1 \\
1 & 1 & 1 & 1 & 1 \\
g_0 & g_1 & g_2 & g_3 & g_4 \\
\cancel{g_5} & \cancel{g_6} & \cancel{g_7} & \cancel{g_8} & \cancel{g_9}
\end{bmatrix}
\begin{bmatrix}
d_0 \\ d_1 \\ d_2 \\ d_3 \\ d_4
\end{bmatrix}
=
\begin{bmatrix}
\cancel{d_0} \\ d_1 \\ d_2 \\ \cancel{d_3} \\ d_4 \\ p_1 \\ p_2 \\ \cancel{p_3}
\end{bmatrix}
$$

Generator Matrix $\times$ data $=$ parity

Erasure coding Decode Illustration

1.

2.



Erasure coding pros/cons

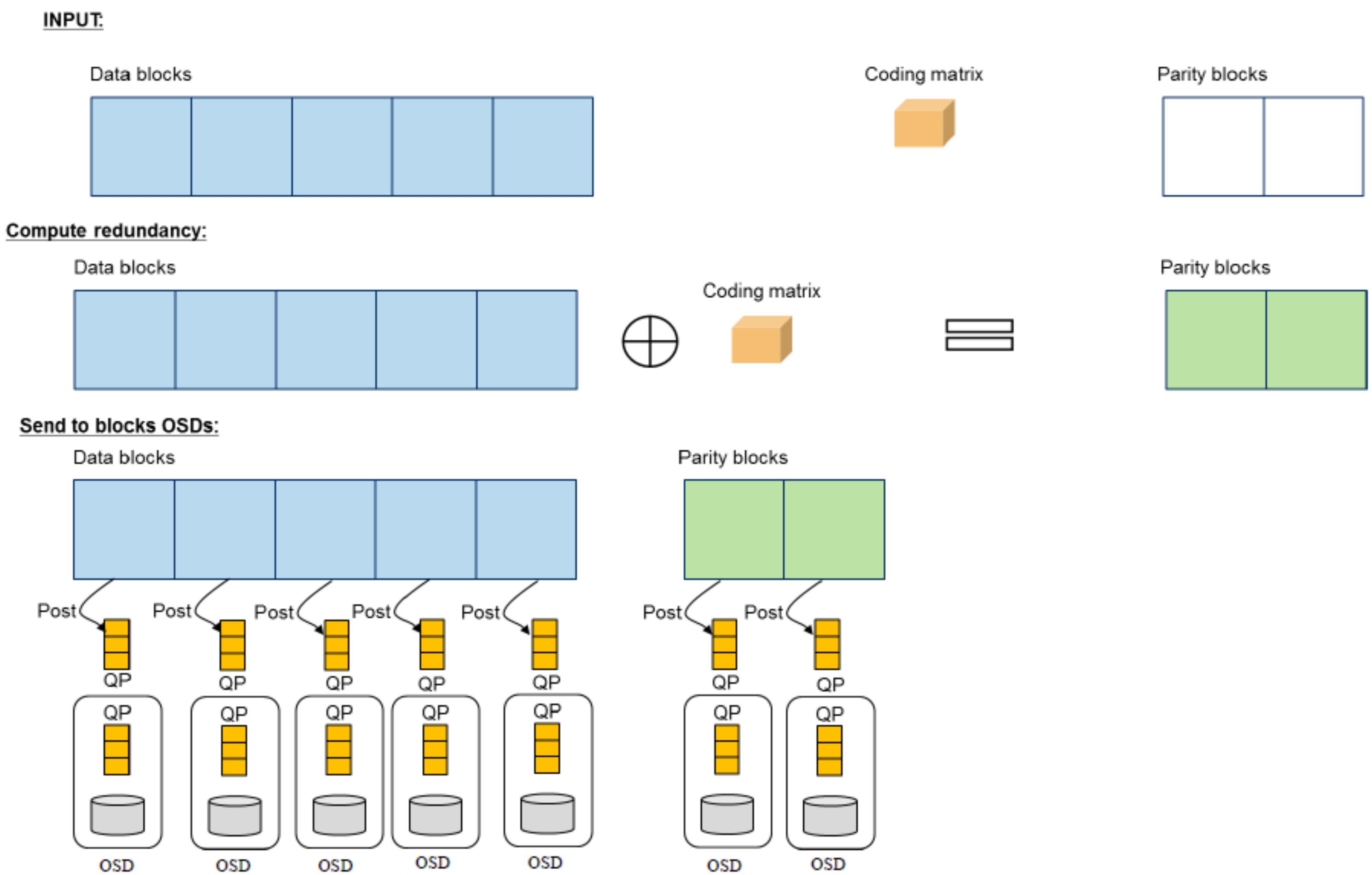
- Pros:
  - *Very* Efficient storage utilization (small storage space for redundancy)
  - *Very* Efficient wire utilization
  - User can choose his configuration (K,M) – no need for multi-level RAID.

- Cons:
  - Large computation overhead needed to generate the redundancy metadata blocks
  - Large computation overhead needed to reconstruct the original data

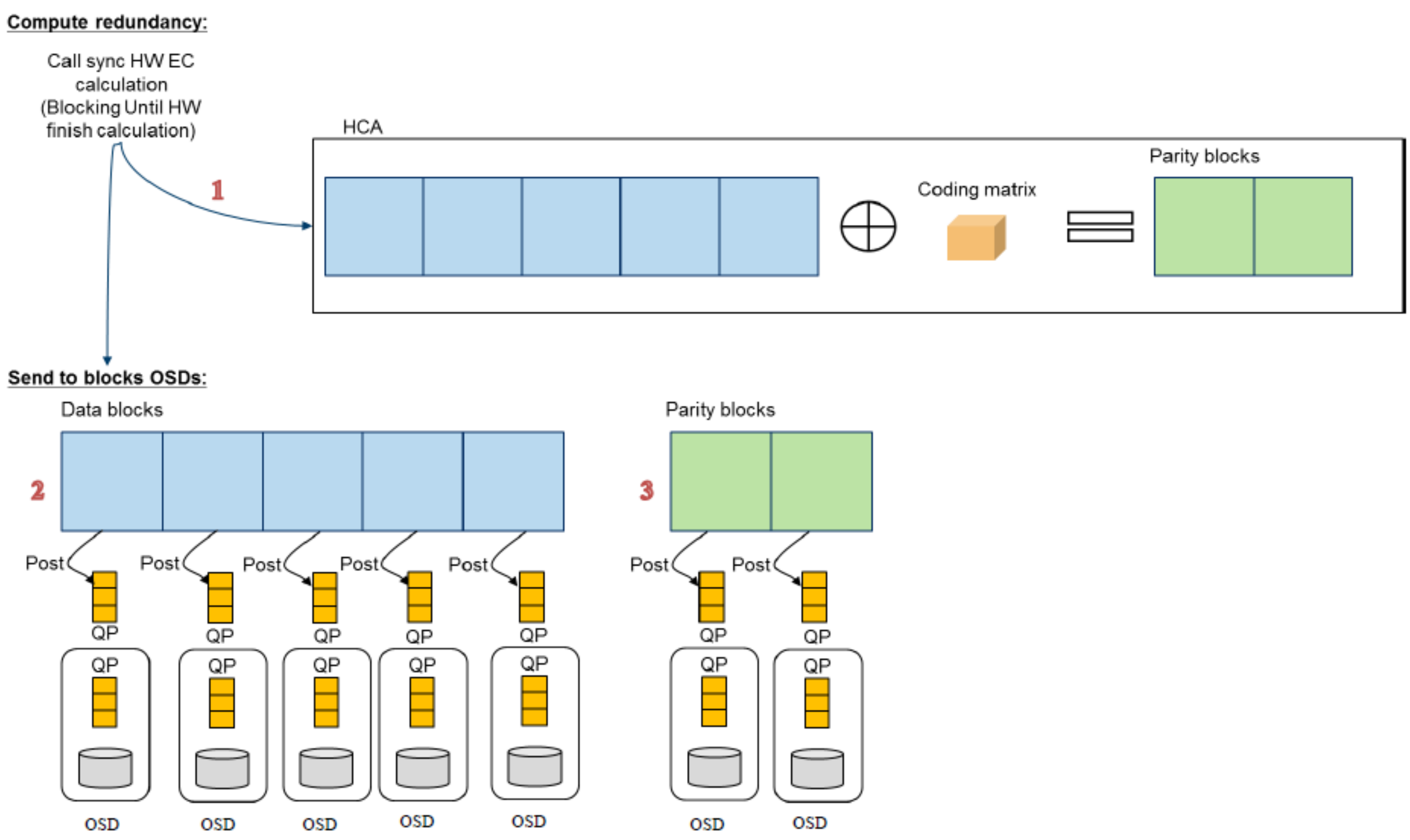
RDMA Erasure coding offload

- Erasure codes calculations is CPU intensive.
- Next generation HCAs can offer a calculation engine.
- These HCAs can also offer a coherent calculation and networking solutions.

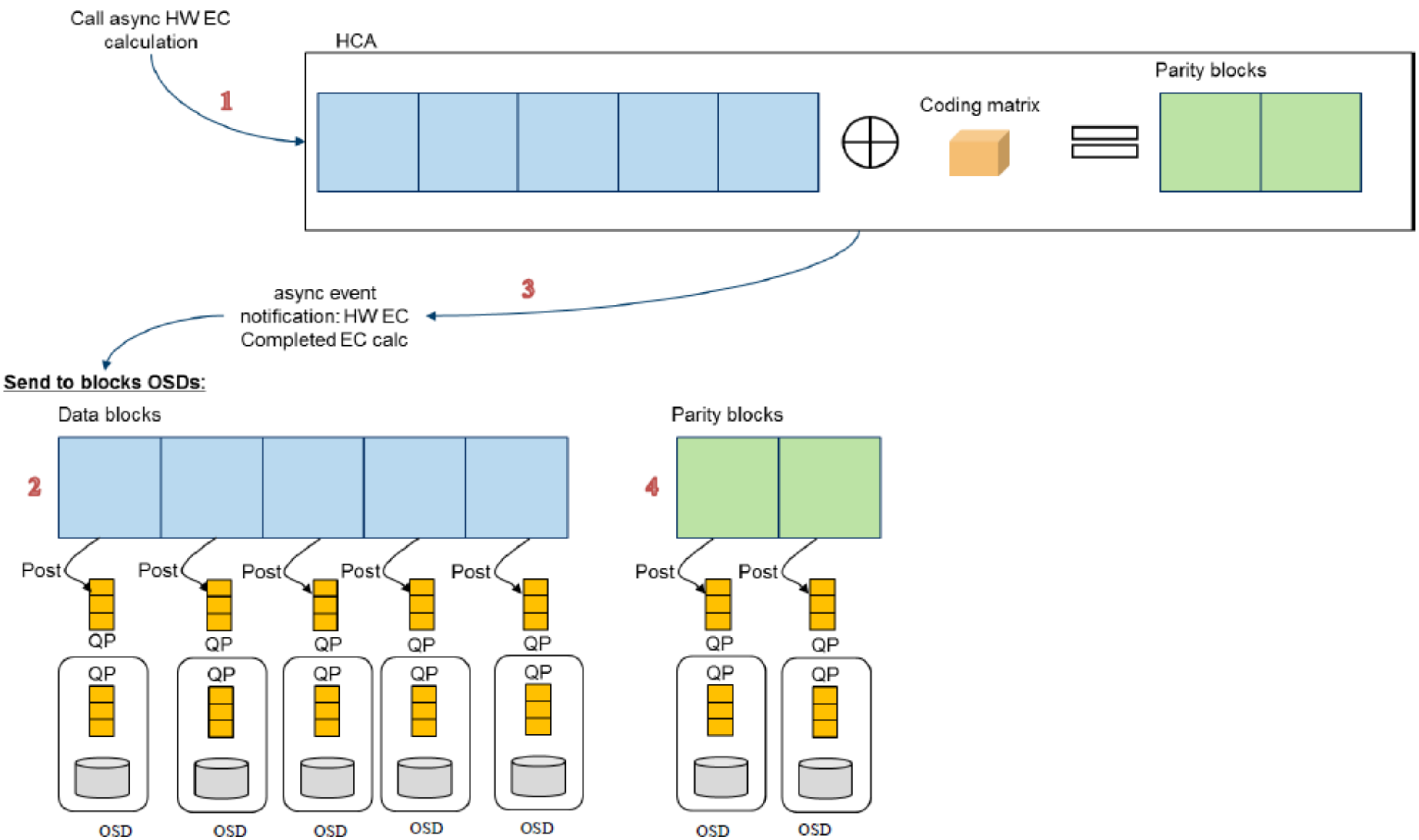
Programming model - SW



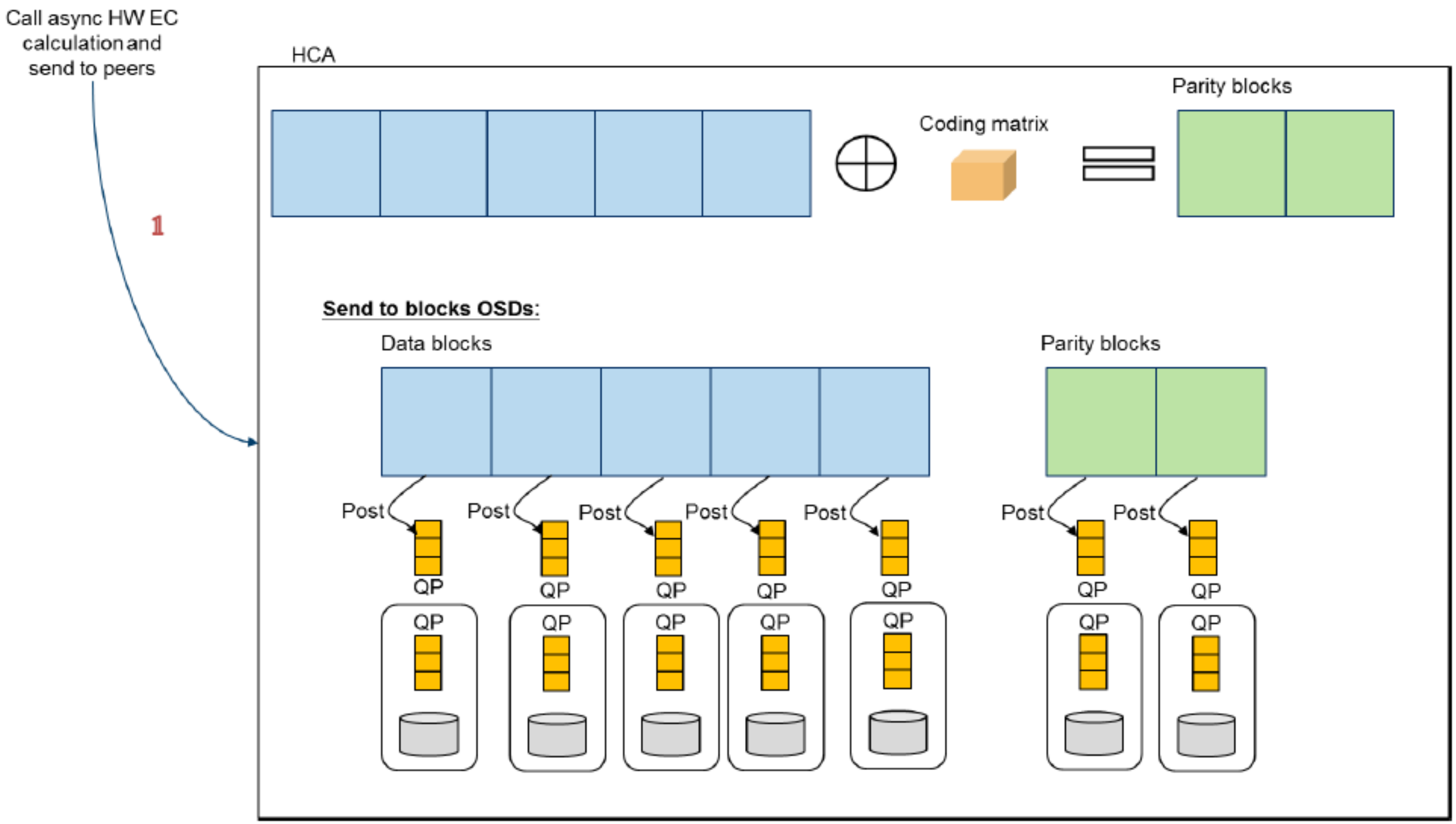
Programming model - Synchronous



Programming model - Asynchronous



Programming model – Full striping



API – Erasure coding context

- EC context verbs representation

```
/**
 * struct ibv_exp_ec_calc - erasure coding engine context
 *
 * @pd:                     protection domain
 */
struct ibv exp ec calc {
        struct ibv pd            *pd;
};
```

- Allocation/Deallocation API

```
/*
 * ibv_exp_alloc_ec_calc() - allocate an erasure coding
 *     calculation offload context
 * @pd:           user allocated protection domain
 * @attrs:        initialization attributes
 *
 * Returns handle handle to the EC calculation APIs
 */
struct ibv_exp_ec_calc *
ibv_exp_alloc_ec_calc(struct ibv_pd *pd,
                      struct ibv_exp_ec_calc_init_attr *attr);
```

```
/*
 * ibv_exp_dealloc_ec_calc() - free an erasure coding
 *     calculation offload context
 * @ec_calc:       ec context
 */
void ibv_exp_dealloc_ec_calc(struct ibv_exp_ec_calc *calc);
```

API – EC init attributes

```
/**
 * struct ibv_exp_ec_calc_init_attr - erasure coding engine
 *     initialization attributes
 *
 * @comp_mask:             compatibility bitmask
 * @max_inflight_calcs:    maximum inflight calculations
 * @k:                     number of data blocks
 * @m:                     number of code blocks
 * @w:                     Galois field symbol size - GF(2^w)
 * @max_data_sge:          maximum data sg elements to be used for encode/decode
 * @max_code_sge:          maximum code sg elements to be used for encode/decode
 * @block_size:            data/code block size
 * @encode_matrix:         buffer contains the encoding matrix
 * @affinity_hint:         affinity hint for asynchronous calcs completion
 *                         steering.
 * @polling:               polling mode (if set no completions will be generated
 *                         by events).
 */
struct ibv_exp_ec_calc_init_attr {
        uint32_t                comp_mask;
        uint32_t                max_inflight_calcs;
        int                     k;
        int                     m;
        int                     w;
        int                     max_data_sge;
        int                     max_code_sge;
        uint8_t                 *encode_matrix;
        int                     affinity_hint;
        int                     polling;
};
```

API – EC memory layout

```
/**
 * struct ibv_exp_ec_mem - erasure coding memory layout context
 *
 * @data_blocks:          array of data sg elements
 * @num_data_sge:         number of data sg elements
 * @code_blocks:          array of code sg elements
 * @num_code_sge:         number of code sg elements
 * @block_size:           logical block size
 */
struct ibv_exp_ec_mem {
        struct ibv_sge              *data_blocks;
        int                         num_data_sge;
        struct ibv_sge              *code_blocks;
        int                         num_code_sge;
        int                         block_size;
};
```

API – Synchronous Encode

```
/**
 * ibv_exp_ec_encode_sync() - synchronous encode of given data blocks
 *    and place in code_blocks
 * @ec_calc:             erasure coding calculation engine
 * @ec_mem:              erasure coding memory layout
 *
 * Restrictions:
 * - ec_calc is an initialized erasure coding calc engine structure
 * - ec_mem.data_blocks sg array must describe the data memory
 *   layout, the total length of the sg elements must satisfy
 *   k * ec_mem.block_size.
 * - ec_mem.num_data_sg must not exceed the calc max_data_sge
 * - ec_mem.code_blocks sg array must describe the code memory
 *   layout, the total length of the sg elements must satisfy
 *   m * ec_mem.block_size.
 * - ec_mem.num_code_sg must not exceed the calc max_code_sge
 *
 * Returns 0 on success, non-zero on failure.
 *
 */
int ibv_exp_ec_encode_sync(struct ibv_exp_ec_calc *calc,
                           struct ibv_exp_ec_mem *ec_mem)
```

API – Asynchronous Encode

```
/**
 * struct ibv_exp_ec_comp - completion context of EC calculation
 *
 * @done:       function handle of the EC calculation completion
 * @status:     status of the EC calculation
 *
 * The consumer is expected to embed this structure in his calculation context
 * so that the user context would be acquired back using offsetof()
 */
struct ibv_exp_ec_comp {
        void (*done)(struct ibv_exp_ec_comp *comp);
        enum ibv_exp_ec_status status;
};
```

```
/**
 * enum ibv_exp_ec_status - EC calculation status
 *
 * @IBV_EXP_EC_CALC_SUCCESS:   EC calc operation succeeded
 * @IBV_EXP_EC_CALC_FAIL:      EC calc operation failed
 */
enum ibv_exp_ec_status {
        IBV_EXP_EC_CALC_SUCCESS,
        IBV_EXP_EC_CALC_FAIL,
};
```

API – Asynchronous Encode

```
/**
 * ibv_exp_ec_encode_async() - asynchronous encode of given data bloks
 *    and place in code_blocks
 * @ec_calc:          erasure coding calculation engine
 * @ec_mem:           erasure coding memory layout
 * @ec_comp:          EC calculation completion context
 *
 * Restrictions:
 * - ec_calc is an initialized erasure coding calc engine structure
 * - ec_mem.data_blocks sg array must describe the data memory
 *   layout, the total length of the sg elements must satisfy
 *   k * ec_mem.block_size.
 * - ec_mem.num_data_sg must not exceed the calc max_data_sge
 * - ec_mem.code_blocks sg array must describe the code memory
 *   layout, the total length of the sg elements must satisfy
 *   m * ec_mem.block_size.
 * - ec_mem.num_code_sg must not exceed the calc max_code_sge
 *
 * Notes:
 * The ec_calc will perform the erasure coding calc operation,
 * once it completes, it will call ec_comp->done() handle.
 * The caller will take it from there.
 */
int ibv_exp_ec_encode_async(struct ibv_exp_ec_calc *calc,
                            struct ibv_exp_ec_mem *ec_mem,
                            struct ibv_exp_ec_comp *ec_comp);
```

API – Verbs stripe object

- In order to perform the full striping operation via a single API call we need to provide our strping layout (who gets what)

```
/**
 * struct ibv_exp_ec_stripe - erasure coding stripe descriptor
 *
 * @qp:     queue-pair connected to the relevant peer
 * @wr:     send work request - can either be a RDMA wr or a SEND
 */
struct ibv_exp_ec_stripe {
        ibv_qp          *qp;
        ibv_send_wr     *wr;
};
```

API – Encode + Transfer

```
/**
 * ibv_exp_ec_encode_send() - encode a given set of data blocks
 *    and place and send the data and code blocks to the wire with the qps array.
 * @ec_calc:           erasure coding calculation engine
 * @ec_mem:            erasure coding memory layout context
 * @data_stripes:      array of stripe handles, each represents a data block channel
 * @code_stripes:      array of qp handles, each represents a code block channel
 *
 * Restrictions:
 * - ec_calc is an initialized erasure coding calc engine structure
 * - ec_mem.data_blocks sg array must describe the data memory
 *   layout, the total length of the sg elements must satisfy
 *   k * ec_mem.block_size.
 * - ec_mem.num_data_sg must not exceed the calc max_data_sge
 * - ec_mem.code_blocks sg array must describe the code memory
 *   layout, the total length of the sg elements must satisfy
 *   m * ec_mem.block_size.
 * - ec_mem.num_code_sg must not exceed the calc max_code_sge
 *
 * Returns 0 on success, or non-zero on failure with a corresponding
 * errno.
 */
int ibv_exp_ec_encode_send(struct ibv_exp_ec_calc *ec_calc,
                           struct ibv_exp_ec_mem *ec_mem,
                           struct ibv_ec_stripe *data_stripes,
                           struct ibv_ec_stripe *code_stripes);
);
```

API – Synchronous Decode

```
/**
 * ibv_exp_ec_decode_sync() - decode a given set of data blocks
 *    and code_blocks and place into output recovery blocks
 * @ec_calc:          erasure coding calculation engine
 * @ec_mem:           erasure coding memory layout
 * @erasures:         bitmap of which blocks were erased and needs to be recovered
 * @decode_matrix:    registered buffer of the decode matrix
 *
 * Restrictions:
 * - ec_calc is an initialized erasure coding calc engine structure
 * - ec_mem.data_blocks sg array must describe the data memory
 *   layout, the total length of the sg elements must satisfy
 *   k * ec_mem.block_size.
 * - ec_mem.num_data_sg must not exceed the calc max_data_sge
 * - ec_mem.code_blocks sg array must describe the code memory
 *   layout, the total length of the sg elements must satisfy
 *   number of missing blocks * ec_mem.block_size.
 * - ec_mem.num_code_sg must not exceed the calc max_code_sge
 * - erasures bitmask consists of the survived and erased blocks.
 *   The first k LS bits stand for the k data blocks followed by
 *   m bits that stand for the code blocks. All the other bits are
 *   ignored.
 *
 * Returns 0 on success, or non-zero on failure with a corresponding
 * errno.
 */
int ibv_exp_ec_decode_sync(struct ibv_exp_ec_calc *calc,
                           struct ibv_exp_ec_mem *ec_mem,
                           uint32_t erasures,
                           uint8_t *decode_matrix);
```

API – Asynchronous Decode

- Pretty much the same idea

```
int ibv_exp_ec_decode_async(struct ibv_exp_ec_calc *calc,
                            struct ibv_exp_ec_mem *ec_mem,
                            uint32_t erasures,
                            uint8_t *decode_matrix,
                            struct ibv_exp_ec_comp *ec_comp);
```

Thank You

OPENFABRICS ALLIANCE

10TH ANNUAL INTERNATIONAL DEVELOPER WORKSHOP