A Fault Resilient Approach to Non-collective Communication Creation in MPI

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Abstract. The increasing size of HPC architectures makes the faults’ presence an eventuality more and more frequent. This is especially relevant since MPI, the de-facto standard for inter-process communication lacks proper fault management functionalities. The past efforts produced extensions to the MPI standard that enabled fault management, the most important one being ULFM. In this paper, we introduce the support for non-collective communication creation (MPI_Comm_create_group) in ULFM to improve the fault management capabilities. We integrate our solution into the Legio library and measure the overhead introduced in the application. The proposed solution removes the possibility of turning the execution into a deadlock after a fault and can be used as an inspiring effort to improve the ULFM repair capabilities.

Keywords: Fault Management · MPI · ULFM

1 Introduction

Computational science applications require more and more resources for their computation, leading to the growth of current HPC systems in terms of performance, energy efficiency and complexity. HPC systems will reach the exascale boundary in the next years (10^{18} FLOPS) [1], bringing more performance but additional issues. With the increase in sizes comes a greater probability of faults, and HPC systems (and their applications) must be able to handle them.

The absence of fault management techniques can make the execution difficult on HPC clusters since the mean time to failure is in the order of days [13]. Future systems will probably lower this value, making it almost impossible for an application to complete without incurring an error. If there are no fault management techniques, the execution terminates without producing results, causing waste of energy and costs. Reports [6] show that the impact of faults is already relevant in HPC. This concept also comes from the fact that the Message Passing Interface (MPI) [4], the de-facto standard for inter-process communication, lacks fault management techniques. The last version of the standard (4.0) tried to reduce the possible sources of faults, isolating them into a single process when possible. While removing the impact of faults in local functions, it does not avoid
their propagation with communication and does not provide a way to repair the execution.

This issue has been hugely discussed in the past, producing MPI implementations able to deal with the fault presence \cite{3,8,7}. Most of them received limited support and did not solve the problem entirely and efficiently. The issue currently receiving the most attention is the User-Level Fault Mitigation (ULFM) MPI extension \cite{2}. It consists of a collection of functions that enable the user to detect fault presence, repair the affected structures and continue the execution seamlessly. Among the added functionalities of ULFM, there are the \textit{shrink} and \textit{agree} functions, that enable communicator reparation and resilient agreement respectively. ULFM is currently integrated directly into the latest versions of OpenMPI, one of the most used MPI implementations.

Many efforts started from the functionalities introduced by ULFM to produce frameworks able to provide checkpoint and restart (C/R) with automatic rollback \cite{9,13,17}. Others leveraged those capabilities to isolate the failed process from the execution, limiting the effect of the fault \cite{14,15}. Nonetheless, the possibilities introduced by ULFM are limited by a few constraints: the reparation process is always collective and currently involves only communicators. We tried to remove these constraints in our previous work \cite{15}, developing support for files, windows and local repair. Still, many other functionalities require additional attention.

In this effort, we analyze the non-collective call \texttt{MPI\_Comm\_create\_group}, which represents a challenge due to its non-collectiveness. Previous works have already shown the relevance of this call \cite{5}, and it has been in the MPI standard since version 3.0. Most of the ULFM functionalities are hard to use due to the non-collectiveness of the operation which prevents the repair. Moreover, the failure of one of the participating processes may lead to deadlock, which is always an undesirable behaviour.

The contributions of this paper are the following:

- We analyze the effects of faults on the \texttt{MPI\_Comm\_create\_group} function;
- We design and implement a solution that removes the main criticalities of the function;
- We integrate the solution into the Legio framework and evaluate the introduced overhead.

The paper is structured as follows: Section 2 shows the efforts that tried to deal with faults using ULFM and emphasizes the works done to improve it. Section 3 shows the behaviour of non-collective operations and our proposed solution to make them fault tolerant. Section 4 covers the experimental campaign done to evaluate the overhead and the scalability of the proposed solution. Lastly, Section 5 concludes the paper.

## 2 Background and previous work

The failure of an MPI process can have a remarkable impact on an application execution since the MPI standard does not specify the behaviour of the survivor
processes. The last version of the MPI standard (4.0) introduced new functionalities to simplify the handling of faults, limiting their impact while possible. While providing ways to represent and react to faults, the standard still does not contain a defined method to recover the execution from them and only allows the application to terminate gracefully.

One of the most relevant efforts that enable the continuation of the execution is ULFM [2]. It is an MPI standard extension proposal that focuses on fault detection, propagation and reparation. While still under development, the ULFM extension got included in the latest versions of OpenMPI, one of the most used MPI implementations. The idea behind ULFM is to provide the user with the possibility to manage faults by themselves. The latter is achieved with changes in the application code that introduce the ULFM functions. This approach allows maximum flexibility in fault management at the cost of additional integration complexity: the programmer must know how and when to handle faults, which is non-trivial.

ULFM by itself does not provide recovery mechanisms, so it is necessary to combine it with other solutions for consistent post-failure execution. The main direction adopted in the literature is in combining ULFM and a C/R utility into a single framework, that introduces fault tolerance (the ability to nullify the effect of a fault) in generic MPI applications [3] [6] [7] [10] [13]. The solution proposed in these efforts is similar: the execution restarts from the last consistent state, removing the impact of the fault. The integration with the application is more intuitive than using ULFM directly since it hides the complexity within the combined framework. Some efforts [13] [12] do not require changes in the application since they leverage a heuristic code analysis to choose the best integration between their framework and the application.

Our previous work proposed Legio [15], a library that introduces fault resiliency (the ability to overcome a fault) in embarrassingly parallel applications. Applications using Legio continue after the fault detection, but the failed process will not resume: the execution proceeds only with the survivor processes, causing a loss of correctness but a faster recovery. These characteristics make Legio ideal for approximate computing applications, where the algorithms already trade correctness for speed. Moreover, Legio extends the capabilities of ULFM by supporting one-sided communication and filesystem functions. Applications leveraging those functionalities can fully benefit from the additional fault management. The integration of Legio with the application leverages the PMPI layer defined in the MPI standard: this allows for seamless integration with no code changes needed.

Apart from Legio, few efforts aim at enhancing the fault management possibilities of ULFM. Most of them focus on improving the performance of ULFM [11] rather than introducing new functionalities. The focus on fault management for non-collective communicator creation is something missing in the literature, despite the promising result of their use [3]. In this work, we introduce the support for non-collective communicator creation into the Legio library.
3 Non-collective operations

A non-collective operation involves many processes inside a communicator, not necessarily all. In the MPI standard, there are a few examples of non-collective calls, one of those is the MPI_Comm_create_group call. First proposed in [5], it got introduced with version 3.0 of the standard. The function creates a communicator containing only the processes present in the group structure passed as a parameter. This function must be called only by the processes part of the group, not by all the ones participating in the communicator (differently from the MPI_Comm_create function). Its non-collectiveness makes the ULFM solution not sufficient: the agreement function and the shrink one presented in the ULFM standard are collective and may require support from processes not involved in the communicator creation. Forcing those processes to collaborate loses the benefits of non-collective communicator creation (less synchronization), so it is not feasible. In general, to implement the non-collective call we cannot use any collective operation, including most of the ULFM ones, windows and file operations.

We conducted some experiments to understand the behaviour of the non-collective call in presence of faults. To better represent the occurrence of a fault in a communicator, we describe it as either faulty or failed. In particular, faulty communicators contain some failed processes but their failure has not been acknowledged by any process. When a process discovers the failure, the communicator becomes failed and the propagation of the failure begins. Our tests proved that:

- The non-collective call works on faulty communicators as long as no process part of the group failed;
- The non-collective call deadlocks on faulty communicators if one process part of the group failed;
- The function fails on failed communicators, returning the ULFM-defined error code MPIX_ERR_PROC_FAILED.

The main criticality of the non-collective call behaviour resides in the second case: while it is possible to handle the error and repair the communicators in later calls, the deadlock prevents us from any interaction and irremediably compromises the execution of the entire application. This effort aims to remove the deadlock eventuality from the application behaviour by changing the parameters passed to the function.

The function MPI_Comm_create_group takes three parameters, which are the communicator to generate the new one from, the group of processes that participate in the call, and a tag used to classify the calls. We may have to change the communicator parameter: previous faults may have already caused the communicator to shrink so we exchange it with the shrunk one. This step introduces the possibility that a process part of the group is not part of the communicator since a previous shrink operation removed it. To solve this issue we need to remove those processes from the group. Figure [1] contains an example of this first filtering process. This first exchange of parameters allows us to limit the impact
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Fig. 1. The reduction of the communicator and group parameters achieved in the first filtering process. All the processes are represented as small circles with their rank written within. The ones filled in red failed. Process 5 failed but its failure has not been discovered yet. The black rectangle represents the communicator, the blue one the one used after the filtering phase. The red rectangle represents the group, the green one the one used after the first filtering phase.

of previously fixed faults, but it does not help in the case of unfixed ones: in the example shown in Figure 1 process 5 is still involved in the non-collective call despite being failed, eventually leading to the deadlock of the execution.

To identify which processes failed within the filtered group, we need all the processes to discover whose of them are still alive. If the call was a collective operation, we could have leveraged the MPI Allgather function: each process could share its rank with the others and obtain data about all the processes sharing. However, the non-collectiveness of the operation forces us to define an algorithm using point-to-point communication only, so we defined a tree-based algorithm. We will first describe the algorithm in a fault-free scenario and then discuss the modifications needed for its fault management.

In a fault-free scenario, the algorithm behaves similarly to the tree reduction algorithm followed by a tree broadcast. The two phases are not distinct in our implementation: each process starts the broadcast after it has completed the reduction, but it does not imply that all the others are in the same situation. Figure 2 shows how the algorithm works considering the time dimension. The algorithm works in a fault-free scenario but it is not sufficient in a faulty environment: a failed process may block the propagation towards the root in the gathering phase and the diffusion of the collected data in the broadcast phase. Figure 3 emphasises this phenomenon, showing how the result obtained is different among the nodes, creating a partition of the network.

To fix the network splitting problem, we integrated into the above algorithm a mechanism to bypass the failed nodes. In particular, the proposed approach
**Fig. 2.** A representation of the algorithm used to remove the presence of failed processes inside the group. Each column represents a process, while green rectangles contain the data held by it. Black boxes represent MPI operations, with the first character showing the type (Send/Recv) and the second the rank of the other process.

**Fig. 3.** The figure shows the algorithm depicted in Figure 2 in presence of faults. Failed processes have their column filled in red, and also MPI calls failing.

works as follows: if a node fails, the next one in its subtree of competency (the subtree having that process as root) will take its place. If that process fails too, then the next one will take their place, and so on. This solution ensures that if there is at least a process in a subtree whose root failed, it will reach and be reachable by all the others. This approach requires that the processes can
learn the liveness of the others with point-to-point communication. Following the analyses shown in [15], we know that the MPIRecv fails if the sender stops working. We use the receive function for communication and fault checking, and we integrate the leader escalation system into our algorithm, obtaining a result shown in Figure 4. The figure shows that all the nodes get the same results, and no partitions are present.

The above solution with the fix of the network splitting allows us to solve the deadlock problem since all the processes can operate on the survivor subset of the group parameter. The only drawback is that the possible faults discovered in the fix are propagated to all the nodes involved, turning the faulty communicator into a failed one. This occurrence causes the function to complete with an error despite the removal of the failed processes from the parameters: nonetheless, we think that the deadlock removal is a crucial step for the function usage in a faulty scenario. Moreover, the MPI_Comm_create function can be used as a non-collective error checker since it will return an error in case of fault presence, and it will work fine otherwise. This is an improvement from the possibilities of ULFM, allowing for error checking in a group of processes in logarithmic time complexity.

4 Experimental campaign

We implemented the proposed solution in the Legio library, and we conducted some experiments to measure its scalability and impact on performance. We ran those experiments on the Marconi100 cluster at CINECA over nodes with 2 x IBM POWER9 AC922 16 cores 3.1 GHz processors and 256 GB of RAM. Every experiment featured 32 processes per node, a single process per physical core.
We made a set of initial runs in a fault-free scenario to derive a basing value (the time needed for the operation without our solution). We performed other tests injecting single process failures, showing how the execution would deadlock and how our solution manages to continue (despite raising an error).

In the experimental campaign, we measure the execution time of the non-collective call integrated with the proposed solution. We run this experiment with varying network sizes (composed of 32, 64, 128, 256 or 512 MPI processes) and group sizes (from 1/32 to the entire network size). We execute the non-collective call 1000 times, measuring the total time needed to complete this task. We perform this measurement both with and without our solution, to better evaluate the impact it has on the execution time. The campaign aims to measure the overhead introduced and prove its logarithmic growth with regard to the dimension of the group.

Figure 5 shows the evolution of the overhead over different group sizes in various networks. The image shows the logarithmic growth of the algorithm, which seems more influenced by the size of the network rather than the group size. While the overhead is not negligible, its scalability is still remarkable. Moreover, the non-collectiveness of the operation reduces the overhead impact: using it removes unneeded synchronization, which can enable faster execution to compensate for the additional communication.

While the results are promising, we think that it is possible to achieve lower overheads by supporting non-collective communication creation directly inside the ULFM implementation, removing the deadlock occurrence and simplifying
the communication. Moreover, it may be possible to make the call work on failed communicators as long as the processes inside the group are alive.

5 Conclusions

In this paper, we discussed the support for non-collective communicator creation calls in ULFM. We highlighted the possibility of deadlocks in case of faults in the involved processes, and we designed an algorithm to avoid that occurrence. We integrated our solution into the Legio library to provide it transparently to the MPI applications. Our proposed solution proved scalable and the overhead introduced acceptable, but we think it can improve by integrating support for the non-collective communication calls directly inside the ULFM implementation.

The support for the non-collective communicator creation call directly in the ULFM implementation can be a relevant feature. It would enable both the fault-proof usage of the call and could also be used for non-collective communicator substitution, removing the constraint of collectiveness in the repair procedure. We think that this last achievement could greatly improve the capabilities of ULFM, introducing non-collective repair of communicators, a feature already requested in literature [15,10].

Future work includes the support of additional MPI functionalities still not handled by ULFM. Moreover, we are exploring the possibility to combine Legio with C/R by applying it only to critical nodes to reduce the impact on the filesystem.

References

1. Amarasinghe, S., Campbell, D., Carlson, W., Chien, A., Dally, W., Elnohazy, E., Hall, M., Harrison, R., Harrod, W., Hill, K., et al.: Exascale software study: Software challenges in extreme scale systems. DARPA IPTO, Air Force Research Labs, Tech. Rep pp. 1–153 (2009)
2. Bland, W., Bouteiller, A., Herault, T., Bosilca, G., Dongarra, J.: Post-failure recovery of mpi communication capability: Design and rationale. The International Journal of High Performance Computing Applications 27(3), 244–254 (2013)
3. Bouteiller, A., Herault, T., Krawezik, G., Lemarinier, P., Cappello, F.: Mpi-v project: A multiprotocol automatic fault-tolerant mpi. The International Journal of High Performance Computing Applications 20(3), 319–333 (2006)
4. Clarke, L., Glendinning, I., Hempel, R.: The mpi message passing interface standard. In: Programming environments for massively parallel distributed systems, pp. 213–218. Springer (1994)
5. Dinan, J., Krishnamoorthy, S., Balaji, P., Hammond, J.R., Krishnan, M., Tipparaju, V., Vishnu, A.: Noncollective communicator creation in mpi. In: European MPI Users' Group Meeting. pp. 282–291. Springer (2011)
6. Egwutuoha, I.P., Levy, D., Selic, B., Chen, S.: A survey of fault tolerance mechanisms and checkpoint/restart implementations for high performance computing systems. The Journal of Supercomputing 65(3), 1302–1326 (2013)
7. Fagg, G.E., Dongarra, J.J.: Ft-mpi: Fault tolerant mpi, supporting dynamic applications in a dynamic world. In: European Parallel Virtual Machine/Message Passing Interface Users’ Group Meeting. pp. 346–353. Springer (2000)

8. Ferreira, K., Riesen, R., Oldfield, R., Stearley, J., Laros, J., Pedretti, K., Brightwell, R.: rmpi: increasing fault resiliency in a message-passing environment. Sandia National Laboratories, Albuquerque, NM, Tech. Rep. SAND2011-2488 (2011)

9. Gamell, M., Katz, D.S., Kolla, H., Chen, J., Klasky, S., Parashar, M.: Exploring automatic, online failure recovery for scientific applications at extreme scales. In: SC’14: Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis. pp. 895–906. IEEE (2014)

10. Gamell, M., Teranishi, K., Heroux, M.A., Mayo, J., Kolla, H., Chen, J., Parashar, M.: Local recovery and failure masking for stencil-based applications at extreme scales. In: SC’15: Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis. pp. 1–12. IEEE (2015)

11. Laguna, I., Richards, D.F., Gamblin, T., Schulz, M., de Supinski, B.R., Mohror, K., Pritchard, H.: Evaluating and extending user-level fault tolerance in mpi applications. The International Journal of High Performance Computing Applications 30(3), 305–319 (2016). https://doi.org/10.1177/1094342015623623

12. Losada, N., Bosilca, G., Bouteiller, A., González, P., Martín, M.J.: Local rollback for resilient mpi applications with application-level checkpointing and message logging. Future Generation Computer Systems 91, 450–464 (2019)

13. Losada, N., Cores, I., Martín, M.J., González, P.: Resilient mpi applications using an application-level checkpointing framework and ulfm. The Journal of Supercomputing 73(1), 100–113 (2017)

14. Pauli, S., Arbenz, P., Schwab, C.: Intrinsic fault tolerance of multilevel monte carlo methods. Journal of Parallel and Distributed Computing 84, 24–36 (2015)

15. Rocco, R., Gadioli, D., Palermo, G.: Legio: fault resiliency for embarrassingly parallel mpi applications. The Journal of Supercomputing pp. 1–21 (2021)

16. Shahzad, F., Thies, J., Kreutzer, M., Zeiser, T., Hager, G., Wellein, G.: Craft: A library for easier application-level checkpoint/restart and automatic fault tolerance. IEEE Transactions on Parallel and Distributed Systems 30(3), 501–514 (2018)

17. Teranishi, K., Heroux, M.A.: Toward local failure local recovery resilience model using mpi-ulfm. In: Proceedings of the 21st european mpi users’ group meeting. pp. 51–56 (2014)

18. Zheng, G., Ni, X., Kalé, L.V.: A scalable double in-memory checkpoint and restart scheme towards exascale. In: IEEE/IFIP International Conference on Dependable Systems and Networks Workshops (DSN 2012). pp. 1–6. IEEE (2012)