（ 続紙 1 ）

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論文題目	Resource Allocation in Network Function Virtualization with Workload-Dependent Unavailability （負荷依存の不可用性を伴うネットワーク機能仮想化における資源割り当て）		

（論文内容の要旨）

Network Function Virtualization (NFV) has transformed network services by shifting from dedicated hardware to virtualized functionalities, thus eliminating the constraints and expenses of traditional systems. Through NFV, computational resources can be pooled, offering enhanced scalability, flexibility, and cost-efficiency. Traditional network functions like firewalls and load balancers are virtualized for deployment on virtual machines and containers. Efficient resource allocation is vital for optimizing network performance, ensuring availability, and meeting agreements. Properly managing resources can enhance the overall efficiency and responsiveness of the service and maintain uninterrupted functionality. Node failures and resource backups impact service reliability and continuity. Resource backups, such as cold and hot backups, enable recovery and minimize downtime. However, challenges arise from many factors like backup strategies, utilization ratio, failure probabilities, recovery strategies, and shared protection, necessitating innovative approaches to balance resource sharing, recovery time, and availability. To tackle these issues, the thesis introduces optimization models and algorithms. This thesis consists of nine chapters.

Chapter 1 introduces the background of resource allocation for higher availability and fault tolerance with workload-dependent unavailability.

Chapter 2 investigates the related works in literature.

Chapter 3 proposes an optimization model to derive a primary and single backup resource allocation considering a workload-dependent failure probability to minimize the maximum expected unavailable time (MEUT). The proposed model adopts hot and cold backup strategies to provide protection. The optimization problem is formulated as a mixed integer linear programming (MILP) problem. This work proves that MEUT of the proposed model is equal to the smaller value between the two MEUTs obtained by applying only hot backup and cold backup strategies with the same total requested load. A heuristic algorithm inspired by the water-filling algorithm is developed with the proved theorem. The numerical results show that the proposed model suppresses MEUT compared with the conventional model. The developed heuristic algorithm is approximately 105 times faster than the MILP approach with 10−2 performance penalty on MEUT.

Chapter 4 proposes a multiple backup resource allocation model to minimize MEUT under a protection priority policy with a workload-dependent failure probability. The proposed model adopts hot and cold backup strategies; for protection of each function with multiple backup resources, it is required to adopt a suitable priority policy. This work analyzes the superiority of the protection priority policy for multiple backup resources and provide the theorems that clarify the influence of policies on MEUT. The optimization problem is formulated as an MILP problem. This work proves that the decision version of the multiple resource allocation problem is NP-complete. A heuristic algorithm inspired by the water-filling algorithm is developed. The numerical results show that the proposed model reduces MEUT compared to baselines. The adopted priority policy suppresses MEUT compared with other priority policies. The developed heuristic algorithm is approximately 106 times faster than the MILP approach with 10−4 performance penalty on MEUT.

Chapter 5 proposes a resource allocation model under preventive recovery priority setting to minimize a weighted value of unavailable probability (W-UP) against multiple failures. W-UP considers the probability of unsuccessful recovery and the maximum unavailable probability after recovery among physical nodes. This work introduces a recovery strategy to handle the workload variation which is determined at the operation start time and can be applied for each failure pattern. This work also discusses an approach to obtain unsuccessful recovery probability with considering the maximum number of arbitrary recoverable functions by a set of available nodes. The optimization problem is formulated as an MILP problem. This work develops a heuristic algorithm to solve larger size problems in a practical time. The numerical results observe that the proposed model reduces W-UP compared with baselines.

Chapter 6 proposes a robust function deployment model against uncertain recovery time with satisfying an expected recovery time guarantee in a cost-efficient manner. Multiple functions protected by a node can share the resources to save cost, which also affects the recovery time if the number of unavailable functions is so large that the remaining capacity cannot recover them and causes a waiting procedure. This work introduces an uncertainty set that considers the upper and lower bounds of the recovery time and the upper bound of the average recovery time among nodes. The robust optimization technique is applied to obtain the worst-case expected recovery time under an uncertain recovery time set. With this technique, the model is formulated as an MILP problem. To solve the problem in a practical time, a heuristic algorithm is developed. It reduces the number of active nodes while decreasing the worst-case expected recovery time within the uncertainty set by converting the linear programming problem to a graph problem. The numerical results reveal the superiority of the proposed model by considering the recovery time guarantee, uncertainty set, and shared protection.

Chapter 7 proposes a primary and backup resource allocation model under reliability guarantees to minimize the deployment cost with considering the effect of the assigned workload on recovery time. This work considers multiple states of pre-configuration for each function with different degrees of instantiation, initialization, and synchronization and different recovery times. This work considers that the extra-assigned recovery workload can be adopted, which means that the recovery workload can be scaled, to speed up the recovery, while improving the resource efficiency to fully utilize the idle capacity for faster recovery. On the other aspect, the extra-assigned recovery workload may lead to unsuccessful recovery in a specific failure configuration. The numerical results indicate that the deployment cost is saved on average 19% and 9% with considering the proposed model compared to two baselines that do not consider flexible backup modes and extra-assigned recovery workload, respectively.

Chapter 8 designs and implements a custom resource and controller in Kubernetes to handle primary and backup resources. This custom resource includes different types of Pods: primary, hot backup, and cold backup. The controller oversees these Pods, ensuring they match their desired states. Moreover, deploying and managing functions play a crucial role in enhancing network service continuity and reliability. Kubernetes automates this process, but existing tools lack real-time and optimal function deployment and management. This chapter presents a two-layer controller structure in Kubernetes to achieve efficient function deployment while considering resource migration for optimal allocation. The demonstration validates that the controller automatically manages the resources promptly and correctly.

Finally, Chapter 9 concludes this thesis and discusses the future works to extend this work.

（続紙 2 ）

（論文審査の結果の要旨）

本論文は、ネットワーク機能仮想化（NFV: network function virtualization)における資源のバックアップ戦略、利用率、故障確率、復旧戦略、及び、共有保護などの課題を検討し、資源割り当て問題に焦点を当てて研究を行っている。本研究で得られた成果は以下の通りである。

第一に、負荷依存の故障確率を考慮した現用・予備の資源割り当てを決定するために、最大不可用時間期待値（MEUT: maximum expected unavailable time)を最小化する最適化モデルを提案している。最適化問題は混合整数線形計画（MILP: mixed-integer linear programming）問題として定式化されている。数値計算の結果、提案モデルは従来モデルと比較してMEUTを抑制することが示されている。

第二に、負荷依存の故障確率を有する保護優先度ポリシーの下で、MEUTを最小化する複数バックアップリソース割り当てモデルを提案している。最適化問題はMILP問題として定式化されている。数値結果は、提案モデルがベースラインと比較してMEUTを削減することを示している。また、採用した優先度ポリシーは、他の優先度ポリシーと比較してMEUTを抑制している。

第三に、多重故障に対する利用不可用確率の重み付け値（W-UP: weighted value of unavailable probability）を最小化する資源割り当てモデルを提案している。W-UPは物理ノード間の復旧失敗確率と復旧後の最大利用不可用確率を考慮する。最適化問題はMILP問題として定式化されている。数値計算の結果、提案モデルはベースラインと比較してW-UPを削減することを示している。

第四に、復旧時間期待値を満足する、不確実な復旧時間に対するロバストな機能配備モデルを提案している。提案モデルでは、復旧時間の上限と下限、およびノード間の平均回復時間の上限を考慮する不確定性集合を導入する。ロバスト最適化手法を適用し、不確実な復旧時間集合の下での最悪の復旧時間期待値を求めている。数値計算の結果、提案モデルの優位性を明らかにしている。

第五に、信頼性保証の下で，復旧に要する稼働負荷が復旧時間に与える影響を考慮し、配備コストを最小化する現用・予備資源割り当てモデルを提案している。数値結果は、柔軟なバックアップモードと余分な復旧稼働負荷を考慮しないベースラインと比較して、提案モデルの配備コストが節約されることを示している。

第六に、現用・予備資源を扱うために、Kubernetesのカスタム資源とコントローラを設計し実装している。実証実験では、コントローラが自動的にリソースを迅速かつ正確に管理できていること確認し、これらの実装の有効性を示している。

以上、本論文は負荷依存の不可用性を伴うネットワーク機能仮想化における資源割り当てに関して、適用シナリオに対応した資源割り当てモデルを提案しており、ネットワーク機能仮想化技術の発展に貢献するものである。本論文の内容は、学術上、実用上ともに寄与するところが少なくない。よって、本論文は博士(情報学)の学位論文として価値のあるものとして認める。また、令和6年1月16日、論文内容とそれに関連した事項について試問を行った結果、合格と認めた。また、本論文のインターネットでの全文公表についても支障がないことを確認した。