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Toward Integrating Overlay and Physical Networks for Robust Parallel Processing Architecture

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***Abstract*—Recently, much research attention is paid toward the wide-area parallel processing architectures whereby all the network devices in the entire network execute the "processing function" in order to shorten the completion time of big data mining tasks. Despite some advancement, such architectures still suffer from physical network failures, which lead to the critical service unavailability problem. As a remedy to this problem, an overlay-based parallel processing architecture, where nodes manage each other by employing the overlay network, can achieve higher service availability against small-scale failures. However, the overlay-based parallel processing architecture is not capable of providing data mining services in case of large-scale network failures disrupting the overlay network. To deal with this issue, our article introduces a design methodology of an overlay-based parallel processing architecture based on integration of overlay and physical networks. Additionally, we introduce basic principles based on the design methodology. Through numerical calculation, we evaluate the effectiveness of integration approach on the performance of parallel data processing, i.e., higher service availability against physical network failures while minimizing traffic load.**

***Index Terms*—Big Data, integration of overlay and physical networks, parallel processing architecture, service availability, traffic load.**

I. INTRODUCTION

Recently, the information and communication technologies are penetrating almost every aspect of our entire society at a phenomenal speed. This phenomenon enables people to obtain various types of data generated from the whole society. As a consequence, the need for effective mining of such data that is referred to as the "big data mining" [1] is rapidly growing. In present, big data mining is accomplished by employing Parallel Processing Architectures (PPAs) such as MapReduce, which distributes processing function to distinct nodes for executing data mining at the speed proportional to the number of nodes.

While conventional PPAs are designed based on the assumption that big data mining is executed in a dedicated network environment such as enterprise and data center networks [2], future PPAs are anticipated to be able to distribute the processing function to all network devices on a wide-area network environment including core and access networks [3]. In this architecture, the effective and high-speed data mining can be made possible by utilizing the computational and storage resources of all network devices, e.g., L3 switches, Base Stations (BSs), and user terminals, where their resources will be much more affluent and the communication-links connecting them will have a significantly larger bandwidth. However, the conventional PPAs with a central management scheme lack scalability for wide-area data mining due to the fact that the centralized management causes a bottleneck in the entire system as the number of nodes increases and user terminals dynamically join and leave the network. Additionally, since the master node can be regarded as a single point of failure, the conventional PPAs are not able to ensure the service availability against the failure of the master node.

An overlay-based PPA is a promising architecture, which improves the scalability and service availability for wide-area data mining [4], [5]. In this architecture, all the nodes execute both management and processing functions by using the overlay network, as depicted in Fig. 1. Additionally, because this architecture keeps providing the data mining until the overlay network itself is disrupted, it achieves higher service availability against the failure of the master node. However, the overlay-based PPA cannot ensure the service availability under the environment where a number of nodes cease to function.

In order to effectively deal with the above-mentioned problem, in this article, we present a design methodology for overlay-based PPA that is robust to large-scale failures. In our design methodology, we suggest the importance of a design based on an integration of overlay and physical networks. According to our adopted methodology, we also present the relevant overlay construction and data allocation principles, which can ensure the service availability against a whole range of failures while minimizing the traffic load of the entire network.

The remainder of our article is organized as follows. In Section II, we reveal fundamental research issues involving wide-area PPAs. Then, we survey relevant research works on PPAs for combating the network failure issue in Section III. Section IV presents design methodology for robust PPAs, followed by performance evaluation of our integration approach. Finally, concluding remarks are provided in Section V.

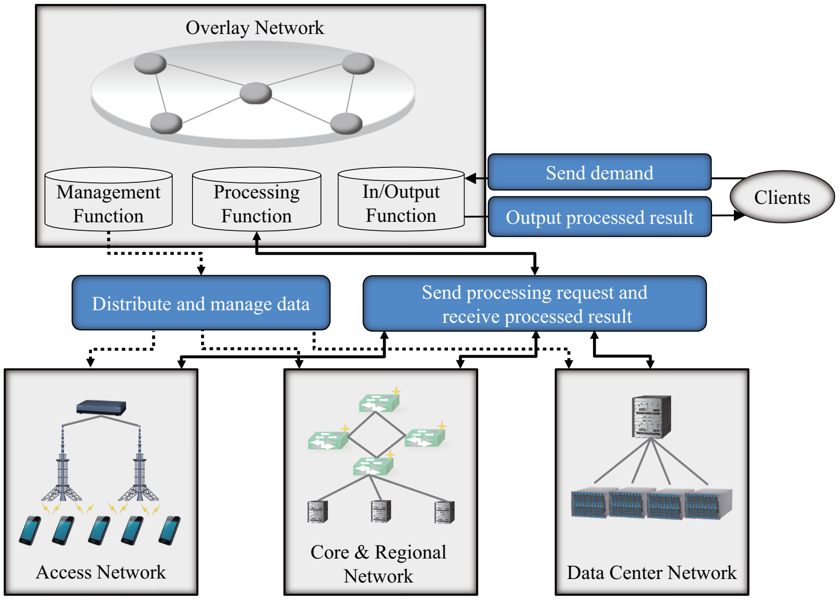


Fig. 1. Our envisioned overlay-based parallel data processing architecture, which distributes all functions to all devices in a wide-area network.

II. FUNDAMENTAL PROBLEM ON WIDE-AREA PARALLEL DATA PROCESSING

While the wide-area parallel data processing is eagerly anticipated for realizing efficient big data mining, it is confronted with a credible threat of various failures in the physical network that will be referred to as the “physical network failure(s)” in short. In this section, we provide a survey of the physical network failures that exist in contemporary literature. Additionally, we discuss the impact of these network failures on the performance of data processing.

A. *Classification of physical network failures*

We explore the probability and scale of physical network failures (i.e., the number of devices, which will be less likely able to communicate due to failure of a network device) in the entire network including the access, regional, core, and data center networks, while the existing taxonomies limit the network area, i.e., data center network [6]. While a network device may cease to function due to various reasons (i.e., Denial-of-Service (DoS) attacks, hardware troubles, software bugs, and so forth), this article mainly covers the hardware troubles and the software bugs.

We show the network failures taxonomy on the entire network based on their scales and probability, as illustrated in Fig. 2. Indeed, hardware troubles and software bugs are one of the main reasons that many user terminals such as smartphones and laptops are prone to failures. The failure of the smartphones per annum is indicated to be around 10% in the report by Square Trade [7], and this probability is stated to be much higher than those associated with other network devices. Additionally, the user terminals tend to be temporarily unable to communicate due to their mobility. In current access networks, because BSs provide communication services, the failure of the user terminals does not affect other devices. However, in the future networking perspective, because Device-to-Device (D2D) communications such as Wi-Fi Direct and Long Term Evolution D2D (LTE D2D) are likely to become promising architectures for forming the user access networks, the failure of the user terminals will have even more impact on the other terminals/devices.

With the failure of BSs in access network, user devices are rendered unable to communicate with others. The current BSs accommodate few hundreds or thousands of users. Their failures have larger impacts than those of the user terminals. According to our survey, the Mean Time Between Failures (MTBF) of the BSs developed by the NTT DOCOMO is arroundd $30,000$ hours [8]. As a consequence, the failure probability of the BSs may be considered as much less than that of the user terminals.

While a regional network concentrates data traffic from the access network, the core network provides communication between the regional networks. Thus, an L3 switch failure on the core network has the biggest impact on other devices. Additionally, the MTBF of the optical L3 switch that is used for regional and core networks ranges from $300,000$ to $800,000$ hours [9]. Since telecommunications carrier generally utilizes a higher reliable switch for the core network, the probability of the switch failing in the core network is lower than that in the regional network.

On the other hand, in the data center network, there are hundreds of thousands of physical servers. Furthermore, in each physical server, hundreds of virtual servers can operate due to the advancement in the virtualization technologies. Thus, it is expected that the impact of the L3 switch failure in the data center network will be larger than that in the regional network. Additionally, the scale of failure of physical servers is situated between the user terminals and BSs. Since the MTBF of the physical servers is around $6,000$ hours [10], the

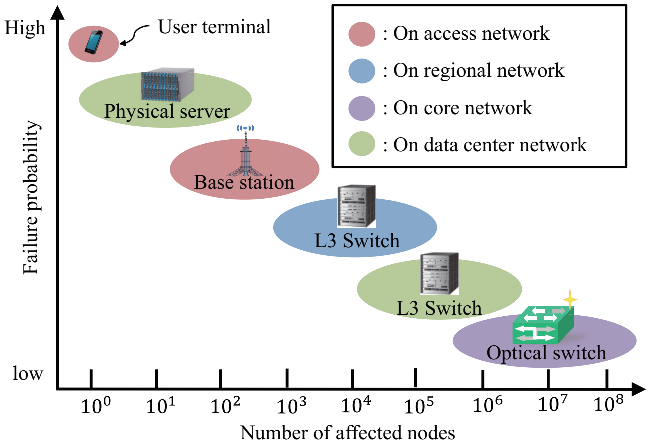


Fig. 2. The network failures taxonomy based on their scale and probability.

probability of failure of physical servers is larger than BSs.

B. Impact of network failures on processing performance

Because distinct nodes decentrally execute data processing, the parallel data processing fails to output the desired result if some processing nodes cease to function. Therefore, in the remainder of this section, we demonstrate the impact of the physical network failures on the processing performance.

The physical network failures drastically decrease the probability of success in the data processing (shortly referred to as the "service availability") because we will be unable to obtain the processed data from some nodes that are unable to communicate with others due to the failure of a gateway device. Additionally, service availability decreases with the increase of the impact of the physical network failures because the number of the processing nodes, which cease to function, increases. Moreover, this architecture does not provide data processing service at all when the master node ceases to function because the master node manages all functionalities of the processing architecture, i.e., management, processing, and in/output functions.

In order to improve the service availability, the common parallel processing architecture replicates processing data and distributes them to distinct nodes. This architecture can output the processed data even if some nodes fail to execute data processing. However, the data replication approach increases the traffic load on each communication-link, and this results in the increase in completion time of data mining. Actually, the MapReduce under the failure-prone environment increases 5% over the normal execution time of data mining due to the increase in the traffic load [11]. Therefore, we need to develop a novel architecture and an effective scheme that improve the service availability while keeping a significantly low traffic load.

III. EXISTING APPROACH FOR PPA ROBUST TO PHYSICAL NETWORK FAILURES

In this section, we introduce the existing techniques that aim to improve tolerance to physical network failures in PPAs. Moreover, we describe the overlay-based PPA, which is capable of overcoming the shortcomings of these existing techniques.

There exist a number of approaches, which address the network failure issue [12]–[14]. For instance, Bressoud *et al.* proposed a check pointing scheme to ensure the processing service even if data processing is disrupted [12]. While this approach can reduce computational resources compared with replication approach, it increases the data traffic for check pointing. Behga *et al.* suggested a prediction approach, which achieves higher throughput under network failure-prone environments [13]. In the work in [14], a task allocation scheme was proposed by taking into consideration the predicted physical network failures. However, the performance is dramatically decreased with large-scale physical network failures. Additionally, all the afore-mentioned approaches cannot provide service when the master node is damaged.

Overlay-based PPAs turn a weakness of these existing approaches into strength [4], [5]. In overlay-based PPAs, the processing function is managed by using the overlay network technology, as explained below. When a data processing request is injected, a node, which received the request, partitions the task into several data blocks. Then, the node selects mappers from the overlay network by using the "flooding" message, and allocates the data block to the mappers. Mappers perform the mapping process, which classifies a large amount of information and picks out the information required for the following process. A mapper that initially finished the mapping process becomes a reducer, and it requests other mappers to transmit the processed data to itself, where the request message is forwarded by using the "flooding" scheme. After receiving the processed data from all the mappers, the reducer executes the reduction process, which integrates the information extracted in the mapping process, and outputs the analyzed result. This architecture is suitable for a wide-area big data mining because it can distribute the management load to all the nodes. Additionally, this architecture succeeds in data mining until the overlay network is disrupted even when some nodes cease to function while the conventional architecture cannot provide service when a master node ceases to function.

Because the connectivity of the overlay network dramatically affects the service availability of data mining, numerous works tackled the connectivity issue from various viewpoints, i.e., graph theory and complex network theory. Indeed, the work in [15] developed the optimal overlay network topology for maximizing the connectivity against two node removal models, i.e., degree dependent and independent removals in the overlay network. However, because the work in [15] assumes the node removal models without taking into account the effect of the physical network failures, the developed overlay networks cannot ensure the connectivity against physical network failures. Therefore, it is essential to design the overlay network by considering the impact of physical network failures on the overlay network.

IV. DESIGN FOR OVERLAY-BASED PPA BASED ON INTEGRATION OF OVERLAY AND PHYSICAL NETWORKS

In this section, we present a design methodology for an overlay-based PPA based on integration of overlay and physical networks. First, we detail our design methodology, which deals with the relevant technical issues. Then, we introduce appropriate overlay network construction and data allocation principles based on our adopted design methodology.

A. Design methodology

The physical network failure does not only lead to the cease of function of the damaged device but also disrupts the communications of the devices, which are connected with the damaged device. In other words, the physical network failure causes numerous nodes to be removed from the overlay network. Therefore, we need to understand the impact of physical network failures on overlay networks (referred to as the "node removal model"). The node removal model can be modeled based on the physical network topology and the probability of physical network failures. Physical network topology can be mathematically modeled by using the degree distribution and degree-degree correlation, while the probability of physical network failures can be formulated with degree of devices in physical network, as shown in Fig. 2. Therefore, node removal model can be constructed by using such parameters.

Based on the node removal model, we can derive an optimal overlay network topology, which maximizes the connectivity of the overlay network against physical network failures. As with the modeling of physical network topology, the overlay network topology is modeled by using the degree distribution and degree-degree correlation. Therefore, we first derive an optimal degree distribution and degree-degree correlation, and then decide the optimal overlay network topology.

Since the overlay network construction scheme decides location of nodes in overlay network, it affects the connectivity against the physical network failure. Therefore, we need to consider the overlay network construction principle by considering the characteristics of the physical network failures such as their scale, probability of failure, locality, and so forth.

Moreover, we should develop the data allocation principle because the data location is important to ensure the data availability. In the overlay-based PPA, data is managed by using the overlay network. Therefore, we develop the data allocation principle by considering the conducted overlay network topology and construction scheme.

B. Overlay network construction principle

Here, we present an overlay network construction principle to achieve higher connectivity against physical network failures. According to our design methodology, because the overlay network construction scheme affects the connectivity of the overlay network, this principle is, indeed, important to design the overlay-based PPA that is tolerant to physical network failures.

The physical network failures have "locality", i.e., the damaged device and other devices that are connected to the damaged device cease to function. Therefore, it is desirable that the devices that are located in the same area (or segmentation) in the physical network become neighboring nodes in the overlay network in order to increase the connectivity against the physical network failures. In this construction principle, because the removed nodes are located in the same area, most of the removed links of the removed nodes are also links to other removed nodes (i.e., there remain a lot of links between the surviving nodes).

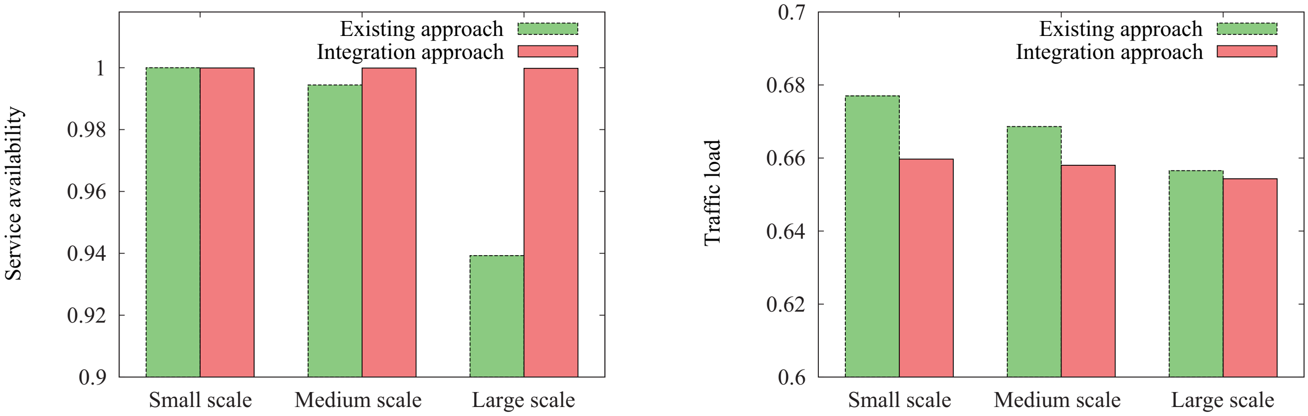
C. Data allocation principle

We present an effective data allocation principle to reduce the traffic load while keeping the service availability. In other words, we explore the mappers' location and the number of data redundancy for the mapping process.

First, we explain a principle to select adequate mappers for minimizing the traffic load of each link while guaranteeing service availability. The overlay-based PPA replicates each data block and distributes the replicated data blocks to distinct nodes. Since the nodes in the same area are removed by physical network failures in the overlay network that is constructed based on the integration approach, it is clearly understood that choosing nodes on the farthest group as mappers ensures the existence of data block against any scale of physical network failures. However, doing so increases the traffic load, which is generated from the mappers to the reducer. Therefore, there is a trade-off relationship between service availability and traffic load in terms of the mappers' location. We can notice that the best solution is to select the mappers by considering the scale of network failures in order to ensure existence of at least 1 redundant data.

This principle can be further improved by considering the functionalities and capabilities of network devices. In wide-area network, there are various types of devices that have different processing power. Due to the fact that the reducer has to wait until all mappers finish their respective mapping processes, choosing mappers that have similar processing power so that all mappers can finish their mapping process at around the same time can increase the effective of resource utilization of the devices.

Then, we present a principle to decide an adequate number of redundant data. In addition to the challenge of dealing with the physical network failures, we consider user mobility. User terminals are prone to communication disruption due to their mobility in the physical network, and are removed from the overlay network. This results in an emergence of isolated nodes and decreases the service availability. Thus, it is required to increase the data redundancy to enhance the service availability. However, this increases the traffic load since extra mappers transmit data to the reducer. As with the mappers' locations, there is a trade-off relationship between service availability and traffic load in terms of data redundancy. Based on disconnection ratio of user terminals and the probability of the network failures, we can decide the optimal number of data redundancy, which minimizes the traffic load while ensuring existence of at least 1 redundant data.



(a) Service availability of data mining

(b) Average traffic load on communications links

Fig. 3. Effect of our integration approach on the capability of data mining in different scales of network failures.

D. Effectiveness of overlay and physical networks integration design

We confirm the effectiveness of our approach in comparison with an existing approach that designs an overlay-based PPA without integrating the overlay and physical networks, i.e., the random neighbor selection and the random data allocation with constant replications. In this performance evaluation, we demonstrate the results of the service availability of data mining and average traffic load on the considered communications links.

We suppose that the physical network follows the power-law degree distribution. The assumed network topology is tree-structured. The number of devices in the physical network is 10^4. The overlay network is constructed based on the topology conducted in the work [15], where the average degree of the overlay network is set to 3. We suppose that a task is partitioned into 5 data blocks and the total number of tasks is 10^3. Because it is generally believed that the mobile users leave the overlay network due to their mobility, we suppose that the 100 nodes leave and join the overlay network. We evaluate the performance of data processing after three types of physical network failures occur, i.e., small, medium, and large scale network failures. These failures result in approximately 100, 1000, and 3000 nodes unable to connect to others, respectively.

Fig. 3(a) demonstrates the effect of our integration approach on service availability in three scales of physical network failures. From the result, it is clearly evident that our integration approach achieves higher service availability and it can ensure approximately 100% availability regardless of the scale of physical network failures. The reason behind the result is that our approach constructs the overlay network by considering the locality of the physical network failures. Additionally, our approach allocates tasks to adequate nodes according to the feature of the physical network failures. Fig. 3(b) depicts the impact of our integration approach on the traffic load of each link in the physical network in the three scales of the physical network failures. It is confirmed that our approach reduces the traffic load of the network regardless of the scale of network failures. In particular, the existing (i.e., conventional) approach consumes more network resources in the case of small scale failures. This happens because the existing approach makes constant replicas without taking into consideration the characteristics of physical network failures, which result in inessential data transmissions. On the other hand, our data allocation principle replicates an adequate number of data automatically. As a consequence, our approach is able to reduce the traffic load in contrast with the existing data allocation scheme.

V. CONCLUSION

In this article, we highlighted the importance of designing appropriate overlay-based parallel big data processing architecture in order to combat various network failures on the entire network. Additionally, we presented two simple yet effective principles, which are designed by integrating topological characteristics between the overlay and physical networks. One is an overlay network construction principle based on node location in the physical network. Another is a data placement principle, which decides the optimal number of replications and data locations by considering the scale and probability of network failures.

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