Distributed Dynamic Failure Detection

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Abstract—Failure monitoring and detection phase is a critical part in providing a scalability, reliability and high availability in current distributed environment. Heartbeat style of interaction is a widely used technique. This technique is utilized for detecting a fault where it monitors the heartbeats of system resources continuously in a very short interval. However, this approach has its limitations as it requires a period of time to detect the faulty node, causing delay in the impending recovery procedures. This paper presents a fault detection mechanism and service using hybrid heartbeat mechanism and dynamic estimated time of arrival (ETA) for each heartbeat message. This technique introduces the use of index server for indexing the transaction and operates dynamic hybrid heartbeat mechanism and pinging procedure for fault detection. The evaluation outcome signifies the use of the hybrid heartbeat mechanism in reducing approximately 30% of the time taken to detect faults compared to existing techniques and provides a basis for a customizable recovery action to take place.

Index Terms—failure detection, fault-tolerance, distributed systems.

I. INTRODUCTION

An effective and efficient Fault tolerant methodology is central in developing reliable dependable systems. Consequently, fault tolerant computing has become an active research area [1][2] and fault detection is the first essential phase for developing any fault tolerance mechanism or fault tolerant systems[3]. Fault detection is the most important aspect of a fault-tolerant distributed system and thus is the standard necessity to achieve scalability, dependability and high availability in distributed environment/systems.

Fault detection identifies and provides information on the faults of the components of these systems[4]. Based on the system design and the assumptions about fault characteristics of components, the study found that fault-detection latencies covered from 55% to 80% of non-functional periods.

This non-functional phase occurs when a system is unaware of a failure (failure detection latency) and periods when a system attempts to recover from a failure (failure-recovery latency)[5][14].

Even though the development of fault detection mechanism in large scale distributed system is subject to active research it still has some lacks[7]. Matthew Gillen et al introduced Scalable, Adaptive, Time-Bounded Node Failure Detection (NFDS)[6]. Since network traffic, CPU load becomes unpredictable. However the paper[7] did not discuss the algorithm on how to tailor the detection time in case of network congestion of CPU overload. The paper only demonstrated the mathematical and experimental comparison across detection time, mistake rate, network bandwidth, and message loss rate.

One of the most popular fault detector service in grid computing is the Globus Heartbeat Monitor (GHM)[7]. GHM provides a fault detection service for applications developed with the Globus toolkit. It was developed under the assumption that both the grid generic server and the heartbeat monitor run reliably[8]. However, few bottlenecks have been identified; GHM scales badly in the number of members that are being monitored[9], requiring developers to implement fault tolerance at the application level which is difficult to implement and does have high-overhead[10]. Failure Detection and Recovery Services (FDS)[11], improves the Globus HBM with early detection of failures in applications, grid middleware and grid resources. The FDS also introduces an efficient and low-overhead multi-layered distributed failure detection service that spare grid users and developers the burden of grid fault detection and fault recovery. However, this technique has a weakness as it requires a period of time before detecting a fault and consequently delays the recovery actions. The problem arises due to the un-indexed status of each transaction and the need to wait for a certain time period.

K. C. W. So, and E. G. proposed latency and bandwidth-minimizing for failure detector and proposed a generic way to detect faulty nodes but exclude flexibility (i.e., ability to support different types of applications)[12]. L. Falai and A. Bondavalli presented an experimental evaluation of different estimations and safety margins of a distributed push failure detector [13].
In this paper, we propose a dynamic failure detection mechanism by integrating dynamic heartbeat detection mechanism with pinging service. In this technique, all the message transactions must be indexed for references and for further action to be taken during recovery process. It is named hybrid due to the integration of pinging to the heartbeat mechanism. We focus on the problem of detecting fail-stop crash failures; a failure in which a crash results in the component to transit permanently to a state that allows other components to presume that it has aborted (e.g., by ceasing to send periodic 'i-am-alive” messages). This research focuses on improving failure detection methodology for a large scale distributed environment. This work also aims at reducing detection time, eliminating false alarm warning, scalability and providing the system with more accurate information for recovery and fault tolerance purposes.

The rest of the paper is organized as follows: Section 2 presents the proposed failure detection mechanism architecture, illustrates the component functionalities to detect the failure as well as failure detection workflow. The comparison with existing technique is demonstrated in Section 3. Section 4 discusses the result analysis. Finally, in Section 5 we conclude the paper.

II. DYNAMIC FRAMEWORK

This section elaborates the dynamic heartbeat framework (DHF) as illustrated in Figure 1. The DHF comprises three main components that are Node Manager (NM), Index Server (IS) and Heartbeat Monitor (HBM).

i) Node Manager (NM)
In order to facilitate the DHF, firstly each member node needs to register itself for inventory at NM. NM provides the means to register a member node to the Index Server by storing and updating the required information to be monitored. Once a node is registered on NM, the information provided by the node will be added and indexed in the Index Manager (IM). The IM will receive notification when the node is added to the index or changed since it was last indexed.

ii) Index Manager (IM)
The IM will be notified each time the NM registers new node or updates the node information since last indexed. This information is automatically updated in IM. During monitoring process, the IM receives a log file generated by the HBM for each heartbeat message

iii) Heartbeat Monitor (HBM)
HBM is responsible for monitoring the state of the registered nodes. In the case of contradiction from their usual behaviors, it will notify the IM so necessary actions can be taken. Each node periodically sends a message indicating its aliveness to the HBM. Then, HBM generates a status to be sent to the Index Server to update the current status of the node. If the HBM does not receive a heartbeat within certain duration $HB_{max}$ the particular node is rendered failed. Accordingly, the IM will provide sufficient information for recovery process after pinging has taken place.

Figure 1. Dynamic failure detection framework

1. A message receiver module in HBM receives heartbeat messages generated by message generator in each node. Each node has their own data receiver placed in individual storage in HBM server. This storage’s identity is established by node ID. For instance, every time node x generates and sends a heartbeat message to HBM a folder for Data receiver allocated for the node in HBM will receive the message.

2. A data collector (DC) component in HBM fetches data from data receiver. The DC keeps track of all registered heartbeat messages and records whenever a heartbeat arrives.

3. A detector component in HBM is responsible for observing the state and identifying failed node(s) based on missing heartbeats. Since the detector has knowledge beforehand of the frequency at which heartbeats are being generated by a registered node, it can decide that the node is having missing heartbeats based on the contradiction with the previous heartbeats. It can interpret the messages embedded in previous heartbeats to resolve the state of the node and summarize the status information.
A. Dynamic Failure Detection

This section discusses failure detection mechanism and how DHF assigns the parameters and estimates the timing of heartbeat arrival. A member node and HBM server are connected by a communication channel. A Node \( n_i \) sends heartbeat messages to HBM. HBM analyses the messages to sort \( n_i \)'s status.

In the following, the algorithm for node failure detection based on dynamic fault detection framework is given:

```plaintext
Detect new monitorable node \( N_x \)
/*check if \( N_x \) register with index log*/
IF \( N_x \) in NM index
    then update index manager \( N++ \);
/* HBw > Hmax allocated, may indicate node problem*/
if \( HBw > H_{\text{MAX}} \)
    ping node
    if ping timeout then
        node \( y \) failed;
        update index manager \( N-- \);
        call fault tolerant service;
    else
        \( H_i = H_{\text{MAX}} \);
    elseif \( H_i < H_{\text{MAX}} \)
        then \( H_i = H_{\text{MAX}} \);
endif
```

Figure 2. Dynamic fault detection algorithm

HBM keeps and manages a list of time intervals of each heartbeat arrival \( B = \{1.003s, 1.90s, 0.062s, 0.893s, 1.922s, 2.007s, \ldots \} \). HBM refers to this list as one of the parameters to compute maximum waiting time \( HB_{\text{max}} \). \( HB_{\text{max}} \) is a maximum inter-arrival time allocated for each heartbeat message extrapolated from the list \( B \). Since network bandwidth and CPU load are unpredictable, this list is the key for HBM to dynamically tailor \( HB_{\text{max}} \) to adapt to changing conditions of the distributed system. HBM constantly reevaluates \( HB_{\text{max}} \) failure detection time to stay relevant to the current condition. This adaptive characteristic essentially reduces the false alarm rate. So we consider the maximum failure detection time to be the largest value in \( B \):

\[
HB_{\text{max}} = \left\{ x \in B \text{ and } x = \text{largest value in } B \right\}
\]

(1)

Along with list of \( B \), HBM also stores the heartbeat interval \( T_i \) (in seconds) and the checkpoint \( T_c \), the timestamp when the last heartbeat was received. This information is the core for HB detection to draw conclusions about a node status.

Basically for the most part, the sending times are influenced by the following environmental conditions:

Network delay Heartbeats time of arrival across a network is affected by network bandwidth and load. It is taken into consideration, that a heartbeat may be delayed due to congested network, therefore \( HB_{\text{max}} \) is adjusted accordingly.

HB message processing delay: a node taking longer to generate and send over a heartbeat, for example, due to processing overload or CPU busy. In many systems, the variations of the inter-arrival times due to processing delays of a node are negligible where this might not affect the \( HB_{\text{max}} \). But when the variations are significant enough, \( HB_{\text{max}} \) would change accordingly.

Based on the data received, and the detection on comparison with \( HB_{\text{max}} \), HBM will generate a suspicion status which indicates whether a node has failed or not.

B. Dynamic Interaction

A member node periodically sends messages which are its heartbeats within maximum time interval allowed. If the HBM does not receive the message after the maximum time interval elapses, the node is suspected to be having fault. Besides the prospect that CPU or network problem causing a node to be unable to send the heartbeat message, it could also be the node messaging/message generator having a problem. In this case the node is active and operational even though the node’s heartbeat processing is having a problem. In this case, a pinging is necessary to invoke the reprocessing of a heartbeat. Integrating ping interaction into DHD can conclude the node status more correctly. Thus this technique is called dynamic heartbeat framework (DHF).

Figure 2. Ping with Heartbeat Mechanism

Figure 2 shows the flow of the fault detection service methodology with heartbeat mechanism. If a heartbeat message exceeded the \( HB_{\text{max}} \), the HBM will ping the member node (the node suspected to be having a problem). If the node does not reply and exceeds ping timeout, the node is considered to be in a failed state, the status of the node will be updated in the Index Server, and consequently, proper recovery action will be carried out.

III. PERFORMANCE

Currently, a widely used heartbeat monitoring technique is Globus heartbeat monitoring\(^2\) (GHM). In this technique, GHM receives heartbeat messages from member nodes at regular intervals. The equation of a normal heartbeat operation without having any failure is given by:

\[
\sum T_n = T_{\text{HM}} + T_i
\]

where,

i) The number of nodes in a grid environment, \( n \).

ii) The interval between each message sent to the heartbeat monitor, \( T_i \).
iii) Time taken for a message to arrive at heartbeat monitor, $T_{HM}$.

The $T_{HM}$ and $T_i$ parameters are set to constants while the number of nodes in the grid environment, $n$ is manipulated to measure the level of effectiveness of the mechanism used in detecting fault at different number of nodes. The number of nodes defines the size of the cluster. The inter arrival times of the heartbeat messages as well as time taken to detect failure of a grid component will be measured.

The GHM failure detection and DHF failure detection processes are demonstrated in Figure 3 and Figure 4 timeline diagrams respectively. A member node in GHM periodically sends heartbeat messages to its HBM.

If the HBM does not receive the message within the time interval, the application is considered to be having a problem. The HBM will wait for another interval to elapse. If the HBM receives the message within the next interval, the Index Server will be updated with the new status of the monitored node i.e. the application is OK. However, if the HBM does not receive the message after the second time interval, the application is declared as failed.

This will take longer time to detect failures and to prove that the node is faulty. The equation of FDS to detect a failure is given by:

$$\sum T_n = T_{HM} + T_i + T_r + T_W$$  \hspace{1cm} (3)

where,

i) The number of nodes in a grid environment, $n$.

ii) Time taken for a message to arrive at heartbeat monitor, $T_{HM}$.

iii) The interval between each message sent to the heartbeat monitor, $T_i$.

iv) The timeout when the heartbeat monitor realizes that it has not received the message from the node, $T_r$.

v) The waiting time of the heartbeat monitor before declaring that the node has died, $T_W$.

vi) The time taken by heartbeat monitor to declare a node has died, $\sum T_n$.

Figure 4 shows the DHF failure detection process that integrates the heartbeat mechanism with the ping mechanism in order to shorten the time taken to detect failure node(s) where waiting for the second interval to elapse is eliminated. The equation of the proposed model is given by:

$$\sum T_n = T_{HM} + T_i + T_r + T_P$$  \hspace{1cm} (4)

where,

i) The number of nodes in a grid environment, $n$.

ii) Time taken for a message to arrive at heartbeat monitor, $T_{HM}$.

iii) The interval between each message sent to the heartbeat monitor, $T_i$.

iv) The timeout when the heartbeat monitor realizes that it has not received the message from the node, $T_r$.

v) The time taken by heartbeat monitor to ping out the suspicious node, $T_P$.

vi) The time taken by heartbeat monitor to declare a node has died, $\sum T_n$.

IV. RESULTS ANALYSIS

The failure detection performance result for GHM is illustrated in Table 1 and Table 2. Table 1 shows the time taken for declaring a failed node by GHM. Table 2 shows the overall time taken to detect the failed nodes within an environment where the number of nodes available varies from 10 to 100. Assuming that 10% of the numbers of nodes available are failed nodes.

### TABLE 1.
THE TIME TAKEN TO DETECT A FAILED NODES BY GHM

<table>
<thead>
<tr>
<th>$T_{HM}$ (ms⁻¹)</th>
<th>$T_i$</th>
<th>$T_w$</th>
<th>$T_r$</th>
<th>$\sum T_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>100</td>
<td>100</td>
<td>20</td>
<td>250</td>
</tr>
</tbody>
</table>

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Table 2. The Time Taken to Detect Failures Based on Number of Nodes, N in the Environment

<table>
<thead>
<tr>
<th>N</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% failure</td>
<td>10</td>
<td>20</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>∑T (ms⁻¹)</td>
<td>25000</td>
<td>50000</td>
<td>125000</td>
<td>150000</td>
<td>175000</td>
<td>250000</td>
</tr>
</tbody>
</table>

Table 3 illustrates the failure detection performance result by DHF while Table 4 shows the overall time taken to detect the failed nodes based on the environment where the number of nodes available varies from 10 to 100. With the assumption that 10% from the numbers of nodes available are failed.

Table 3. The Time Taken for Detecting the Failed Nodes Using the Proposed Mechanism

<table>
<thead>
<tr>
<th>Time (ms⁻¹)</th>
<th>30</th>
<th>100</th>
<th>20</th>
<th>24</th>
<th>174</th>
</tr>
</thead>
<tbody>
<tr>
<td>∑T</td>
<td>17400</td>
<td>34800</td>
<td>87000</td>
<td>184400</td>
<td>121800</td>
</tr>
</tbody>
</table>

Table 4. The Value of N Nodes and Time Taken toDetect Fault Using the DHF

The GHM performance result obtained from Table 2 and DHF performance result from Table 4 are depicted in Figure 5 graph diagram.

Figure 5 show the performance result comparison between GHM and DHF. From this figure, when the number of nodes increases, the time taken to detect the failure nodes is increased. However, DHF required less time taken as compared to GHM because for each suspected failure node DHF does not need to wait for next interval. Alternatively, DHF pings the node to force the node to respond, whereas the GHM mechanism needs to wait for the second interval to confirm the failure state. For example from Table 4, when the number of nodes is 70, DHF model needs only 12180ms of processing time while Table 2 shows that FDS model needs 17500ms. Thus, the result shows that DHF model provides an efficient approach up to approximately 30% better than GHM model.

V. CONCLUSION

This paper demonstrated a framework and algorithm in detecting failure within distributed environment for distributed system highly availability. The performance evaluation has been conducted between current GHM model and the proposed DHF model. The DHF is designed for monitoring current distributed. In this paper, DHF embeded pinging process into its framework and run at low level service thus it will never affect the system protocols and policy in order to avoid future problems. Embedding ping interaction into DHF is very significant in case occasion where a node cannot send the heartbeat message due to HB generator problem. Consequently, DHF can determine a member node status. The process also essential in reducing the detection time and false alarm rate. Furthermore, DHF always dynamically recalculate HBmax failure detection time based on a list of inter-arrival history data. Thus it can reduce the false alarm rate. Overall, This technique able to reduce the communication overhead by shortening the time taken to detect fault in a distributed environment.

REFERENCES


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