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初稿

First draft

蘇適

Penn H. Su

指導教授：許永真 博士

Advisor: Jane Yung-Jen Hsu, Ph.D.

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First draft

本論文係蘇適君 (R99922157) 在國立臺灣大學資訊工程學研究所完成之碩士學位論文，於民國 102 年 1 月 21 日承下列考試委員審查通過及口試及格，特此證明

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Acknowledgments

I'm glad to thank . . .

致謝

感謝...

中文摘要

Abstract

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Chapter 1

Introduction

This chapter provides an overview of the thesis. First, we describe why WSN deployment and maintenance are still difficult, and how an intelligent middleware which employs a new programming model which separates design abstractions between high-level application design and low-level hardware constructs could be addressing the challenge. Next, we describe the needs for fault tolerance and why it is hard on such middleware. Lastly, we describe our proposed solution to this problem.

1.1 Motivation

1.1.1 Wireless Sensor Network Deployment is Hard

Wireless sensor networks are areas filled with network of tiny, resource limited sensors communicating wirelessly. Each sensor is capable of sensing the enviornment in its proximity. Wireless sensor networks are employed in a variety of applications ranging from home automation to millitary.

Sensor networks offer the ability to monitor real-world phenomena in detail and at large scale by embedding devices into the environment. Deployment is about setting up an sensor network in a real-world environment. Deployment is a labor-intensize and cumbersome task since environmental influences or loose program logic in code might trigger bugs or sensor failures that degrade performance in any way that has not been observed during pre-deployment testing in the lab.

The real world has strong influences of the function of a sensor network that could change the quality of wireless communication links, and by putting extreme physical strains on sensor nodes. Laboratory testbed or simulator can only model to a very limited extent of those influences.

There have been several reports on sensor network installations where they encountered problems during their deployment[3][11][2][16][10][13][17][18].

Testbed in laboratory environment can still not model the full extents of the influences a real world enviroment could do. Deployment still a big problem in wireless sensor network applications.

1.1.2 Maintaining WSN deployment

The possibilities of sensor failures is a fundamental characteristic of distributed applications. So it is critical for distributed applications to have the ability to detect and recover from failures automatically, since not only the sensor deployments are usually huge in scale, the deployment are to run unattended for a long period of time.

There have been abundance of research in fault tolerance for wireless sensor network deployments proposing low-level programming abstractions or framework to implement redundancy or replication.[19][9]

1.1.3 Component based middleware for distributed applications

However, the increase in number, size and complexity in WSN applications makes high-level programming an essential needs for development in WSN platforms.

This is supported by several reasons. Firstly, the diversity of hardware and software for WSN platform is as diverse as the programming models for such platforms[14]. Secondly, existing programming models usually sacrifice resource usage with efficiency, which is not suitable for tiny sensors in sensor networks. Thirdly, existing programming models still forces developers to learn low-level languages, which imposes an extra burden to developers, and it goes to show when the reusability for those programming models are low in existing applications.

Software componentization, or lightweight component models, has been recognized to tackle the concerns above. It brings several advantages over past approaches with separate of concern, module reusability, de-coupling, late binding.

The primary advantages of this approach is reconfigability, adaptability in applications like never before, since the high-level components and low-level constructs are loosely decoupled and interpretted by the middleware, high-level application logic can be added functionalities and framework around it without changing the application logic at all, and applications can adapt to different hardware configurations without changing any internal logic.

In Intel-NTU Center Special Interests Group for Context Analysis and Management (SIGCAM), our team have been collaborating on a project, called WuKong, to develop an intelligent middleware for developing, and deploying machine-to-mahicne (M2M) applications. The main contribution of this project is to support inlligent mapping from a high-level flow based program (FBP) to self-identified, context-specific sensors in a target

environment[12].

1.2 Problem definition

1.2.1 Component Based Fault Tolerance System

The development and deployment for a fault tolerant application is still immature in most component based middleware. Even though components are modular in providing reconfigability to applications, they are still not failure resistent and cannot recover from failures. The problem is worsen when the number of components increase in applications, the developers would still bear the burden of manually programming the applications to ensure fault tolerance.

1.3 Proposed Solution

I propose to investigate how applications described in high-level flow based program language could translate to low level constructs to create a fault tolerant, applications in WuKong. In detail, we investigate how system components collaborate to achieve a common goal while satisfying application requirements to achieve self-fault detection, self-fault diagnosis, and self-fault recovery.

With colleagues from the Intel-NTU Special Interests Group for Context Analysis and Management (SIGCAM) at National Taiwan University, I have developed a new intelligent fault tolerance system, called Fur (temp), as part of WuKong project, an Intelligent Middleware for developing and deploying applications on distributed platforms. Our proposed system consists of agents collaborating to simplify fault tolerance development and

to shorten deployment cycle for heterogeneous M2M applications.

The frivolous nature of requirements in applications, and actual physical sensor environements, along with the hard to predict user priorities, each contributes a unique challenge in its flavor to developing an adapatable fault tolerance solution.

Below are the list of areas that this work will address solutions in.

Intelligent Mapping

Flow-Based Programming (FBP) Paradigm has been used in WuKong to enable loosely coupling between high-level application logic and low-level hardware constructs. WuKongs also achieves late-binding to bridge the worlds together at the last stage of deployment using a technique known as intelligent mapping. Intelligent Mapping is a process in which high-level application logics are broken down into components and then mapped to appropriate nodes. Sensor Profile Framework (SPF) are used in mapping to handle heterogeneous sensor platforms, thus applications can be successfully converted into lower hardware constructs to generate low-level intermediate code to deploy to the sensor network.

Sensor Profile Framework

Sensor Profile framework provides an high-level abstraction to sensor capabilities to enable building more complex application logic.[12]

User Policy Framework

Allowing user-friendly specification of application executive objectives, and context-dependent management of system peformance.

Group Communication Systems

A group communication system deals protocols for synchronizing group states

among group members in an consistent manner.[4]. When the applications are deployed to the sensor network, groups will be formed to implement redundancy. For a group of low-power sensor to collaborate on a common goal, along with high-level application requirements and Sensor Profile Framework, a new group communication protocol is needed to support fault tolerence.

1.4 Thesis Organization

Our work overlaps many diverse but interconnected domains, each topic being itself a subject of advanced research and abundant literature. The second chapter gives a brief background overview of these domains. We start by describing wireless sensor networks. Then we go on to discuss fault tolerant design for distributed systems, it's objectives and recent developments. Finally, we will be talking about component model based middleware. The third chapter gives some overview of related work. The following two chapters describe our work in fault tolerance for WuKong system. We first give an overview of some essential components in WuKong. Then we give a comprehensive description of our fault tolerance system architecture. We conclude this chapter by highlighting how the integration of those subsystems, through careful scrutiny, could bring to the development of a fault tolerant WSN application. We then present two experiments to evaluate the performance, correctness of each mechanism in the following chapter. This thesis concludes with a summarization of our proposed system and future work.

Chapter 2

Background

2.1 Wireless Sensor Networks

Sensor nodes are equipped with low-power, low-cost, and failure-prone sensors or actuators. Sensor networks are networks of sensor nodes that connect to the physical space that are intrumented to produce data that could be meaningful for further research. They collaborate to collect, process and disseminate environmental information[1].

Sensor network could be homogeneous, meaning all nodes are identical with same sensors, actuators and hardware setup. Sensor networks could also be heterogeneous where nodes have different sensors, actuators and hardware setup. Heterogeneous networks require higher level management and organization resources. Wireless sensor networks are nodes that communicate through air by sending electronic signals. Wireless communications aren't stable, as it is highly influenced by environmental factors.

2.1.1 Redundancy

Sensor networks are usually deployed in large scale and unattended in long period of time. Sensor networks communicate with low-power wireless radios to aid scientists in collecting spatial data that could lead to more understanding of the environment. However, several challenges such as node failures, message loss, and sensor calibration leaves the effectiveness of sensor networks in question. With the assumption of spare homogeneous resources, redundancy is used in sensor networks to increase fault tolerance against node failures. The system is designed with backup nodes that could automatically recover and replace should one node fail.

2.2 Component Based Middleware

Middleware enables communication and management of data that simplfies complex distributed applications.

As most applications for wireless sensor network involves management of data and communication between network of nodes, middleware is integral in providing a unified experience for implementing more complex architecture such as service-oriented architecture.

However, the separation of design abstractions between low-level hardware and high-level application logic has not been successful in sensor based systems.

It is also not successful in terms of making them adapatable and evolvable for new services in new environments.

2.3 WuKong: The intelligent middleware for M2M applications

2.3.1 Goal

Deployment and development for M2M applications are in its infancy today. As many applications are still single purpose in homogeneous networks with specific network protocols. The hardware has a fixed range of sensors, and the applications cannot be easily ported to other platforms.

The existing middleware support that decouple high-level application design abstractions and low-level hardware has not been successful.

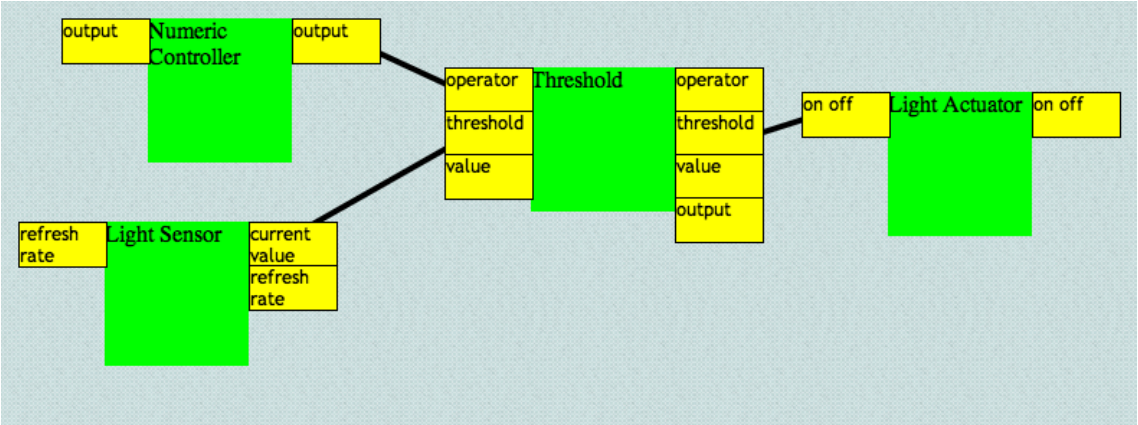
In Intel-NTU Center Special Interests Group for Context Analysis and Management (SIGCAM), we have been collaborating on a project, called WuKong, aiming to develop an intelligent middleware for developing, and deploying machine-to-mahicne (M2M) applications with ease. The main contribution of this project is to support inlligent mapping from a high-level flow based program (FBP) to self-identified, context-specific sensors in a target environment[12].

2.3.2 Flow Based Programming

M2M applications are by definition distributed where the application requirements involve a network of nodes collaborating for some common goals. M2M applications are typically defined by its flow of information between components, as opposed to more traditional applications that focus more on local information processing.

Flow Base Programming is best suited for describing M2M applications as it allows the developers for the applications to focus more on the abstraction meaning of the com-

Figure 2.1: A FBP application



ponents instead letting the unimportant details such as the hardware to stick right in the face. The result application will contain all necessary information for the framework to construct low-level details to implement the flow.

Applications are designed and constructed on FBP canvas by dragging a set of abstract components from the library as illustrated in Figure 2.1 Each component is illustrated by a green block, each block has a set of properties, each with different access modes, such as readonly, writeonly, readwrite. Properties on the left of the greenblocks are properties that could be written, and properties on the right are readable. Components are connected by links, which is drawn by linking two properties in different components.

Some components represent physical hardware such as a sensor, or an actuator while some other components could represent virtual processes such as mathmatical computations, comparisons, etc. However, the final physical implementations of the components are only made during application deployment by the Master but not during FBP construction.

Components expose their interface through properties. A link is only made with properties with matchinkg data type. The FBP applciation in Figure 2.1 illustrates a simple

scenario where the light actuator will turn on the light if light level drops below some value. The Numeric Controller component will be assigned to a user input device used by users to set its desire light threshold, which its output is sent to Threshold component. The light value is sensed from Light Sensor component and sent to Threshold. If the light value sensed is below the threshold value, Threshold will output a boolean to set the on off property of Light Actuator to turn the device, which will be deteremined during deployment, that it is represented by on or off.

2.3.3 Sensor Profile Framework

While FBP defines the logical view of an application, WuKong profile framework allows tracking, identification of physical resources within the Sensor Network. There are a range of sensors which provide similar functionality with different level of quality, it could model the sensor capability to enable handling heterogeneous sensors and provide a common abstraction for the logical view.

There are two main concepts in Sensor Profile Framework, WuClasses and WuObjects. WuClasss model components by exposing a number of properties describing, and allow access to, a specific resource represented by the class. Drawing from the example in Figure 2.1, the on off property of Light Actuator component is boolean writeonly. WuClass also implements an update() function to describe a component's behavior. For example, Threshold has four properties: operator, threshold, value, output. The output value is determined from the previous 3 properties that it returns true when the value is lower or higher than the threshold which depends on the value of the operator, and it returns false otherwise.

WuObjects are the main unit of processing that are hosted on the nodes. Each WuOb-

ject is an instance of WuClasses. It allows the framework to achieve 4 responsibilities:

1. Allow the Master to discover the current status of a node with the list of WuClasses and WuObjects it has.

2. Create new WuObject instances on a node to start receiving data and doing local data processing.

3. Trigger executions in WuObjects, either periodically or as a result of changing inputs.

4. Propagate changes of properties between linked properties in different components, which may be hosted locally or remotely.

Property Propagation

The profile framework is in charge of communication between WuObjects as well, which are not necessarily on the same nodes. Profile Framework monitors the changes in properties and propagate the changes to the connected WuObjects. For example, if a Temperature WuObject is connected to a Threshold WuObject, the changes in Temperature current value property will trigger propagation from the Profile Framework to propagate the new value in current value to the Threshold WuObject connected property, and since Threshold WuObject could be on a different node, the framework will take care of this by initiating a wireless connection between the nodes to send the data over. Once a new value has been set, Threshold WuObject will also trigger its update() function to recompute its output properties which in turn would cause another chain of propagation to the linked WuObjects.

2.3.4 Compilation and Mapping

Figure 2.2: WuKong application build flow

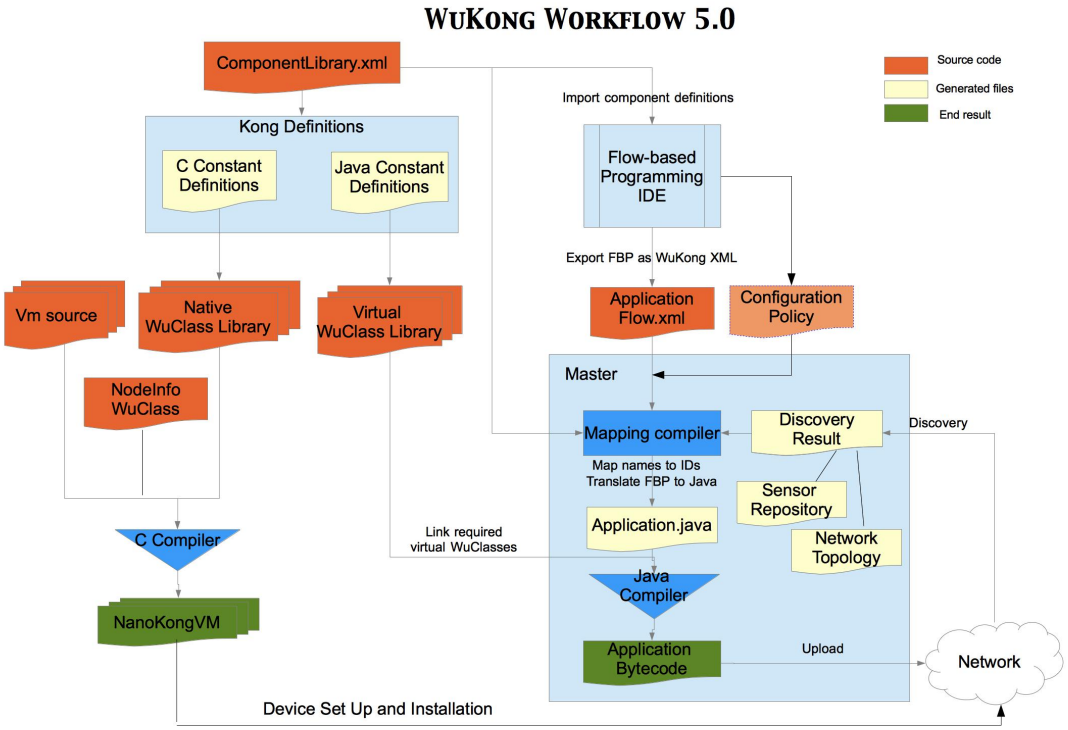


Figure 2.2 shows the overview of WuKong's build flow. The left part represents the build process for NanoKong VM which will be installed on the sensor nodes as part of the WuKong framework. The top part represents the build process for generating component libraries and Virtual WuClass library which will be used in other parts of the process. The right part illustrates the build process for FBP applications from being drawn in the IDE to Java bytecode that will be transmitted to the nodes.

The FBP program from the IDE will be exported as XML to the Master, the Master will then take this XML and passed to Mapper to generate a Java program that will be

executed on the nodes. Finally, the compiled code is then wirelessly uploaded to the nodes in the network.

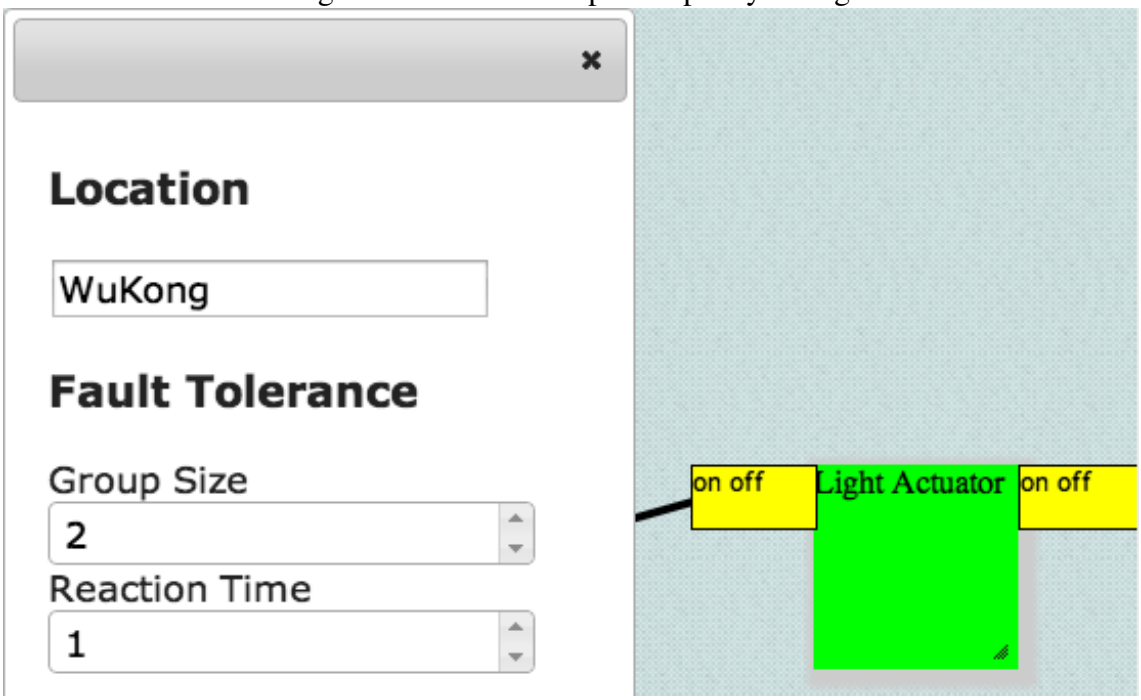
The Java code consists of many parts from different phases of the mapping process. First, the Java code contains information about links between components that were taken from the FBP XML passed in earlier from the IDE. A link contains the source component id, destination component id. The library code for components corresponding to the component ids are stored in the node if it is written in native language, or uploaded as part of the Java bytecode if it is written in Java language. Second, it contains information about the mapping from application component ids to actual node identifications and positions. The purpose of a mapping which separates from the actual link makes it easier to substitude the actual host of the WuObject later during reconfiguration from the Master. This mapping is created by the Master during discovery phase that probe the network for node's capabilities in terms of available WuClasses, then mapper will decide the final candidates that will be hosting for a component. If no native version of a component is found on the nodes, mapper will substitute with a Java version of it.

2.3.5 System Progression Framework

There are a few popular wireless communication protocols in M2M applications: ZigBee, ZWave. It is expected that in the future more diverse wireless nodes equipped with radios that support protocols such as low-power bluebooth and WiFi that all have one or more powerful gateway to connect to the outside world. In WuKong system, one of the gateways will take on the role of higher management decision maker called *Master* to making the decisions for deployment and producing the configuration of wireless sensor networks.

2.3.6 User Policy Framework

Figure 2.3: A user component policy dialog



Many M2M applications are heavily influenced by user preferences and current environmental context, as users and objects are mobile and application requirements and policy could change in time. Users are able to specify user policy for every component in the FBP and the application as a whole as illustrated in Figure 2.3

Fault Tolerance policy

M2M applications are inherently distributed, and hence it is inherently prone to failures since all nodes are running autonomously unattended for a long period of time where the external enviornmental influences could break and shut down the devices easily. Fault Tolerance policy enables users to specify relevent policy for tolerating failures in the

granular level. This thesis will discuss more on fault tolerance policy in the following chapter.

Chapter 3

Related Work

3.1 Component Based Middleware

Distributed Systems such as Wireless Sensor Netweorks (WSNs) composed of multiple resource constrained devices equipped with low-power radios, low-cost sensors collaborating to perform tasks for applications in multiple discipline such as habitat monitoring. However, typically WSN applications are huge in scale, subject to unreliable network, high risk of node failures, and expected to run unattended for a long period of time, several work on lightweight component models have been proposed[5][7][6].

3.1.1 Lightweight Component Models

Work such as LooCI by Hughes et. al.[8] and Remora by Taherkordi et. al.[15] have demonstrated the feasibility of reconfigurable infrastructure with event-driven programming model, event management system, dynamic-binding to reduce development overhead, simplify abstractions, and easier, dynamic reconfiguration for distributed applications.

3.2 Fault Tolerance in Distributed Systems

Many systems has been proposed to provide fault tolerance in distributed systems, as the possibilities partial failures is a fundamental characterisics of distributed systems. However, distributed systems such as Wireless Sensor Networks typically involves a large number of resource-constrained devices equipped with various hardware components such as microprocessors, sensors, memory, wireless communication. An application rely on the collaboration among the sensor nodes in the network to perform tasks.

In order to prevent a single point of failure in applications that would bring application to a halt in the event of failure, one of the primary goals for most of the work for fault tolerance is to eliminiate single point of failure in an application, so replications, redundancies are recognized to be a good model for tackling the problems mentioned earlier in distributed systems. Replication and redundancy are both techniques that allow the system to duplicate multiple copies of a specific system component such that in the event of failure of one of the components, one of the other duplicated components can take over to perform the same services or functionality that the previous one provides.

3.2.1 Service-Oriented Architecture

Neumann et. al.[9] proposed a new redundancy infrastructure to bring Service-oriented Architecture (SOA) to Wireless Sensor Networks (WSN).

SOA is an established approach to ease development of complex distributed applications by encapsulating system compoennts into services, this allows a more flexible way to construct and develop interactions in application.

However, these approaches don't work well with applications where reconfigurability, interoperability, and heterogeneity are requirements. Existing approaches do not consider

reconfigurability in the application level that might invalidate existing infrastructure built upon one instance of applications in another new instance when redeployed. Most existing approaches also are not efficient in providing reducing the development overhead to simplify fault tolerance in existing applications.

Chapter 4

Fur: An Intelligent Fault Tolerance System

This chapter describes how subsystems in Fur collaborate to provide fault tolerance for applications. First we will describe how users could specify fault tolerance policy for the application, and then how WuKong Master take the policy, application and discovery results and compile into low-level intermediate representation that could be deployed to the network. Lastly, we describe how the sensor network detect, recognize, and recover from failures autonomously based on the result of the mapping.

4.1 WuKong Applications

?? illustrates a typical WuKong application with components connecting to form a small network. What this figure shows is that applications are made of components, and components are connected through properties. Any pair of properties form links that binds components together. Connected components interact with each other based on the di-

rection of the connection. The properties on the left of a component are inputs to this component, to the right side are the outputs of an component. Thus one can infer that a connection cannot connect to both inputs or outputs of any pair of components as both of them have the same data flow.

4.2 Fault Tolerance Policy

In this work, fault tolerance policy can only be specified on the level of components, so there is a separate policy for every component. For every compoennt, users can specify two rules to guide and influence how fault tolerance works at the hardware level.

ıum Redundancy Level The minimum number of devices that will be supported as a backup for a particular component. Therefore when one of the devices fail, others will take over.

ıximum Reaction Time The maximum latency a failure will take to detect within the heartbeat group it is detected.

The policy for every component will be taken by the WuKong Master, along with the FBP application and discovery results, to produce the final mapped results that could be compiled into low level bytecode that would be executed on the network.

4.3 Redundancy

The primary design for fault tolerant distributed system is based on the concept of redundancy and distributed systems usually have advantages to have spare resources. Not only it is good to combat partial failures, it also provide durability to the system for an extended period of time.

Spare resources address the first fundanmental characteristics of fault tolerance that there is no single point of failure within the system.

One of the challeneges in producing a fault tolerant design in a heterogeneous network modeled by the WuKong's sensor profile framework is that devices are partially homogeneous, meaning that the hardware setup is different from node to node, so it is not straightforward to simply assign a device as a complete backup of another device.

The solution introduces two new system abstractions that could address the challenge: Recovery chains and heartbeat groups.

4.4 Mapping for a fault tolerant system

The figure **??** above illustrates the essential parts in the mapping process for a fault tolerant system.

Mapping is a process of converting a high level abstractions from FBP with components to low level bytecode representation that will be deployed to the network.

Heartbeat is an important mechanism to detect failure. Our work assume a fail-stop model where sensor nodes fail by not sending messages for a period of time. Mapper will have to determine the heartbeat arrangement, dependencies to ensure every sensor node is monitored and will not fail without notice.

4.4.1 Heartbeat Group

Heartbeat arrangement usually depends on the applications and sensor arrangement **??**, thus most related work aim for a specific type of application and sensor arrangement to simplify heartbeat arrangement, however since application type and sensor arrangement

in WuKong are not known until deployment, therefore a new way to arrange heartbeat has to be devised.

In WuKong, application are drawn on a canvas which consists of blocks that gives the type of sensors or resources needed and lines which connects the resources together in such a way that would satisfy the requirements. However, arranage heartbeat based on the flow of the components is not desirable since applications are not the immediate representation of the underlying network topology such that some components could be mapped on the same node, and some connected components could be mapped to nodes that are far away from each other that require multiple hops to reach. Arrangement based on such high abstractions would incur extra communication overhead by making a lot of nodes as a relay for heartbeats.

The proposed solution will produce application agnostic arrangement and at the same time be used in producing the arrangement of the compoennts in the network to reduce the communication overhead as much as possible.

Assuming that links are symmetrical and toplogy is stable after making the arrangement, we proposes the algorithm below to produce heartbeat arrangement for applications.

The algorithm 1 will produces a clustering with nodes that are one hop distance to each other, in other words, fully connected. By grouping nodes within one hop distance together, we significantly reduce the possibility of heartbeat hopping which is a big factor in communication overhead.

The implementation of the function isNeighbor depends on the actual hardware used, if it is using ZWave, then it will query ZWave for information.

The worst-case time complexity of the algorithm is $O(n^2)$ given a list of disconnected nodes since every single one will form a group of its own, therefore the inner loop will be running for every node in the list, thus it is quadratic.

Algorithm 1 Determine Heartbeat Arrangement

Require: A list N of node ids of the network
Require: A function isNeighbor that returns a boolean for whether a pair of node ids are neighbor
Ensure: A list of lists H which contains the node ids of the groups

```
while |N| > 0 do
    Pick a random i ∈ N as anchor node
    Create a new list h
    Add i to h
    Remove i from N
    for Every n in N do
        if isNeighbor(i, n) then
            Add n to h
            Remove n from N
        end if
    end for
    Append list h to H
end while
```

The best-case time complexity is $O(n)$ when the nodes are fully connected, since the inner loop will be executed only once.

The it is possible that due to some peculiar network topology that the algorithm would produce single node group which itself could not be of any use.

If that happens, the algorithm will be rerun again. Since the anchor is picked randomly from the remaining node list, the algorithm will not produce the same result thus eliminating the problem.

4.4.2 Recovery chains

When a component FT policy indicates a minimum redundancy level higher than one, WuKong Master will map multiple eligible nodes to carry the WuObject coresponding to the component and become the backups in case of a failure.

Since nodes could carry more than one component WuObject, and we assume a het-

erogeneous network where it consists of nodes with different combinations of capabilities, so for every comoponent WuObject there should be an ordered list of nodes like a chain of command that when one of them failed, the next one will be able to replace its place.

When a failure is detected, the detector is not necessarily carrying or knowing what resources there are in the network at the given moment, and it would produce an enormous of overhead to query for the resources in the network, so with this ordered list of recovery, the information could be stored in advance to prevent nodes having to do all the work over and over again whenever a failure is detected.

After mapping, the information of recovery is distributed accordingly based on the heartbeat group results to ensure the integrity of recovery process such that the detector will be able to recover broken links and update the nodes that are affected.

The algorithm to produce the recovery chains is shown below, and it is separated into several sections.

Gather Candidates

First it would have to sort and filter from the list of nodes discovered, which are eligible to provide certain resources for components specified in the application. Once it is sorted out, the algorithm will produce a dictionary of component id as keys and list of node ids as values.

The algorithm requires node info of each node in the network. A node info constitudes information such as a list of WuClasses and a list of WuObjects that are used to help Master greatly in making an informed decision to gather a list of eligible candidates for components.

Function isCapable returns a boolean for whether the node is capable of carrying the component

Algorithm 2 Gather Eligible Candidates for Components

Require: A list C of application component ids
Require: A list I of node ids of the network
Ensure: A dictionary D of component id as keys and list of node ids as values

```
function ISCAPABLE(i, c)
    if ComponentToWuClass(c) in WuClasses(i) then
        return True
    else
        return False
    end if
end function
for Every c in C do
    for Every i in I do
        if isCapable(i, c) then
            Add i to D under component id c as key
        end if
    end for
end for
```

This algorithm will filter out and produce a list of eligible candidates for every application component.

Redundancy Level Enforcement

Once the candidates has been gathered for every compoennt, here it will be doing a check to enforce redundancy level policy to make sure all gathered candidates are above the minimum redundancy level. If any of the candidates is not satisfied, the deployment process will be terminated and the system will send a warning to the users to inform of this situation.

Sort Candidates

It would be perfectly safe to deploy at this point with the unsorted candidates for each component, but it will be running into a problem that could compromise the operation

of the system by unoptimized component arrangement. If the components placement is unsorted, it is possible that unnecessary communication would saturate the system thus compromising the health of the application. On the other hand, if the placement is carefully analyzed, the impact of the overhead could be minimized to certain degrees such that the system could run when deployed.

Algorithm 3 Build histogram of the nodes appear in candidate list

Require: A dictionary D of unsorted recovery chains of every component
Ensure: A dictionary H of node ids and number of occurrances
  for Every c in C **do**
    for Every n in $D[c]$ **do**
      if n not in H **then**
        $H[n] = 1$
      else
        $H[n] = H[n] + 1$
      end if
    end for
  end for

Algorithm 4 Sort Recovery chains

Require: A list C of components
Require: A dictionary D of unsorted recovery chains of every component
Require: A histogram H of all nodes
Ensure: A dictionary D of sorted recovery chains of every component
  for Every c in C **do**
    Sort $D[c]$, and use H as keys in decending order
  end for

By sorting based on the occurrances of node as candidates, the nodes with highest scores will be hosting a lot more components thus reducing external communications within the system especially for the case when WuObjects are linked but are placed in separate nodes.

4.4.3 Determine Heartbeat Group Period

Once the placement and ordering for the components in forms of recover chains are decided, the heartbeat interval for heartbeat groups could be deteremined. Since heartbeat groups could have multiple components, the group heartbeat period is half of the minimum maximum reaction time policy of the components.

Our system assumes a fail-stop model where nodes are suspected dead when it does not send out messages, but to compensate possible deviation in communication latency, a failure is detected when the node does not send a heartbeat message within two normal heartbeat periods. Thus the heartbeat period is half of the reaction time.

Algorithm 5 Determine Group Heartbeat Period

Require: A list of heartbeat groups H
Ensure: A list of heartbeat groups with heartbeat periods
  for Every heartbeat group g in H **do**
    for Every component Component(n in g) **do**
      Find the lowest minimum reaction time
      Divided in hald and assign the period to group g
    end for
  end for

Since all nodes within the heartbeat group is compared against, so only the lowest time will be picked.

4.5 Information Distribution

After mapping and produced heartbeat groups for the network and recovery chains for the components, WuKong would have to generate and assignment information appropriated to every node to support fault tolerance.

Every node will have information pertain to the list below:

1. Recovery chains for the mapped components
2. List of nodes of the heartbeat group it is in
3. The recovery chains of the node it will monitor based on the heartbeat arrangement
4. The application links of the components assigned to the node it will monitor based on the heartbeat arrangement
5. Heartbeat period of the group it is in

4.6 Application generation

WuKong runs a JVM on every node in the network, the VM provides services for the application program in Java to access lower parts of the resources. This section will introduce the list of newly added interfaces and resources to support and enable fault tolerance for the application.

1. component instance id to WuObject address map
2. heartbeat groups member list
3. heartbeat group period list

4.7 Wireless Deployment

The rest of the deployment is the same as the deployment described in the background work for WuKong, where after it generates the Java code, it compiles down to lower byte-code representation and send it to every node wirelessly. The nodes will be reprogrammed by taking the code and reload in their flash memory.

4.8 Fault Tolerance System

Member ranking

If application could specify a full ranking among a group, Whenever a leader died, a member has to replace its position. Leader identification, successor of current leader.

agent should specify whether this group has any ranking rules for a members. Whether there is a full ranking for current members and future members. This could lead to different actions reacting to similar events. ...

4.9 Agent architecture

This section will first go into details of how applications in a form of an abstract graph are being managed in a distributed system after being compiled and transformed into lower bytecode representation, then I will further discuss how the agent architecture on every node collaborate to form groups that will be the basic unit of redundancy in the application to detect sensor failures, diagnosis the failure, and finally recover from failure.

?? illustrates the proposed agent architecture in the sensor network. Every component in the application is converted into groups, which consists one or more nodes, and one of them is a leader. Every group has only one leader. Heartbeats are sent out from the members and leaders to monitor each other.

4.9.1 Autonomous Systems

Sensor networks composed of a large number of diverse subsystems. Subsystems intertwined with complex relationships that prohibit human intervention. Subsystems such as deployment, operation, reconfiguration, maintenance must be automated.

The inability, passiveness to errors makes the past systems unable to deal with perturbations, or unpredictable changes in the environment. Such systems know a limited amount of patterns and trigger predefined actions when they encounter these patterns. In order to make system adapt to new environment in a way similar to biological systems, they need to react to events as a whole in real-time.

4.9.2 Distributed agents

As our system consists of complex elements and subsystems mingled together, an appropriate way to handle complex behaviors in decentralized systems is to based it on a society of agents. [**?**]

4.9.3 Towards failure detection

As we mentioned earlier why sensor systems has to evolve to adapt to crutial, ever changing environment, one of the first things a system could achieve that goal is to detect failures autonomously.

Group membership

In our model, sensor networks consists of a diverse of sensor platforms, and some subset of sensor nodes are equipped with similar sensors situated near each other.

Since sensor networks are inheritly concurrent, it is very hard to reason about the states of the nodes in a distributed fashion. In order to provide fault tolerance in the system, a number of nodes need to be in sync and form a group to monitor and replace faulty node if necessary.

?? illustrates a running applications with three components: Temperature, Light and

Threshold. Every component is implemented by a group of sensors hosting the same object that represents the component.

Every node consists of two agents, namely membership and controller as illustrated in the **??**. When application is deployed, every node is populated with a link table full of links and a list of objects representing the components on the application that are being assigned to.

Membership agent is there to maintain and update the membership list by also managing a watchlist and a reportlist to receive/send heartbeat from/to.

Heartbeat and node failure A failure in distributed system could come from different sources. Some nodes might fail because of software bugs; some nodes might fail because of poor wireless link quality caused by interference. One of the biggest challenges in distributed systems is to be able to detect the types of failures when it occurs correctly. Pulled between efficiency and reliability, decisions to make individual sensor nodes at the same time able to detect failures with knowledge of others but also have to reduce the amount of resources is essential for designing a effective distributed system.

There is another type of failures caused by a completely different reasons. Byzentine failures are failures inspired by the Byzentine General's Problem where components of a system fail in arbitrary ways (besides stopping or crashing) by processing requests incorrectly, corrupting local states, or producing incorrect or inconsistent outputs.

As we assume society of cooperative agents, every agent in the system will strive to be helpful, and share a common goal. This is strengthen by the fact that the agent goals' are bootstrapped from a common source which is the WuKong Master. However, nodes could still fail. In order to be consistent, we model failure by whether a node could send messages or not. This is called a fail-stop failure model.

A fail-stop failure model is a model in which sensor nodes are suspected of failure when they stop sending messages which could caused by multitude of reasons such as network partition, or software bugs.

Heartbeats are messages sent by individual nodes periodically to indicate to the monitoring nodes its health [].

?? illustrates some nodes sending heartbeats that detects a failure when a number of expected consecutive heartbeats have not been received.

A node is considered dead when it has not been sending heartbeats for more than 2 rounds of timeout.

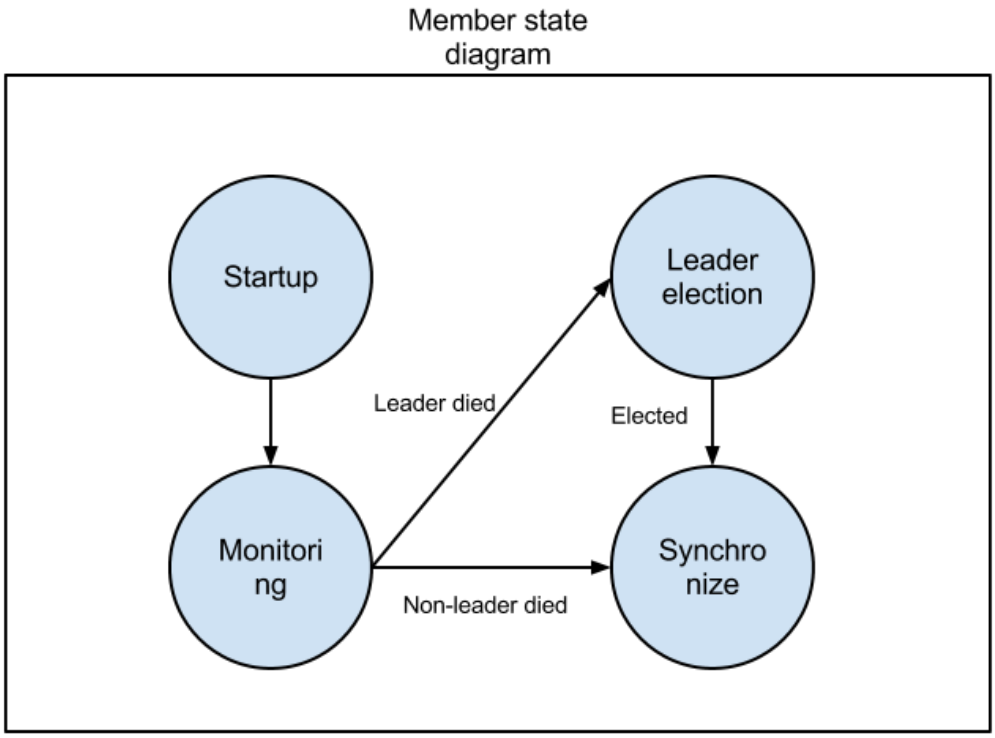
Group setup The WuKong Master has already assigned an ordered list of nodes for every component, every node would be able to know who are in their group for any particular component.

Wielded with this knowledge, membership agent will setup all heartbeat links between the nodes if not already.

Since the setup is asynchronous without lockstep, all nodes are free to do whatever they want while others are being programmed. We added a random backoff after the nodes are programmed to prevent the problem of nodes reporting failure when they startup, because when the node finished setup, the nodes it is watching might not be finished reprogramming, thus it will delay its heartbeat and exceed the timeout causing the node to send false alarm.

As illustrated by **??**, every node has a leader which is elected when the group is formed.

Figure 4.1: Node states



Connecting them up

When a node failed, or has not sent heartbeats for too long, a node failure will be picked up by the monitoring nodes. However, a system is not fault tolerant if it cannot decide who could be replacing the failing component. So there must be some way to organize groups such that when a failure is detected, a replacement could be decided.

It is possible that there will be multiple failures occurred in a timely fashion. We need to be able to detect all possible failures within a group, so we need a heartbeat network.

Of course the structure of heartbeat communication pattern highly depends on the underlying network assumption and infrastructure of the application. To produce the

most efficient network with the least connections, heartbeat network has to satisfy two properties.

1. Every node has to monitor at least one node other than itself

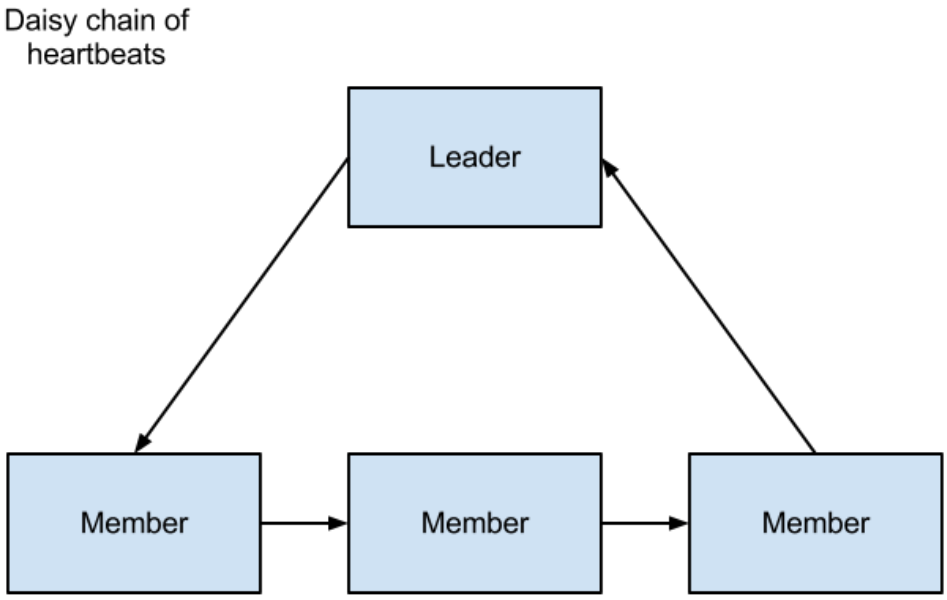
2. Every node can only has one node monitoring itself

A heartbeat network in the form of a daisy chain is one of the networks that satisfy both properties as shown in 4.9.3. Every daisy chain heartbeat network monitors all nodes in the group, given by the properties that every node has to monitor at least one node and every node can only have one node monitor itself. So if there is n nodes, there can be at most n nodes being monitored, every monitoring node can only monitor one node, every node can only monitor node that others have not, thus every node is monitored by only one unique node. Thus this daisy chain guarantees every failure can be detected.

Message complexity Every heartbeat takes one message to send from one to another. As of current, we assume every heartbeat is sent using unicast, and there is no ACK for heartbeat messages. The message complexity for standard one-hop star network takes about O(2n-2) messages since the leader sends n-1 to every member and every member would also has to send a message back to leader, that comes to double of the single traversal from leader to other members.

The message complexity for the daisy loop takes about O(n) messages for a group, because every member only sends one heartbeat to one other member at a time including the leader.

Figure 4.2: Daisy Chain of heartbeats



4.9.4 Failure recovery

When a node failed, it is guaranteed that at least one node will detect this. However, the chain is broken, and it would be impossible for the membership agent in the node to decide what the subsequent actions could be. They are not designed to do such things. There need to have another agent to decide based on local information the actions to take to resolve this issue.

Link table entry protocol

When the application is deployed, every operating node contains at least one object that represents one component in the application. To connect the objects just like what it did in the application as shown in FBP needs a table to store the information of the links. Link table is broken down into two layers, where the top layer gives the information between two components, and the bottom layer gives a list of nodes that are part of the same group that could provide the service for operating the application. By breaking into two layers gives us immense flexibility to handle many different kinds of graph that the FBP could produce.

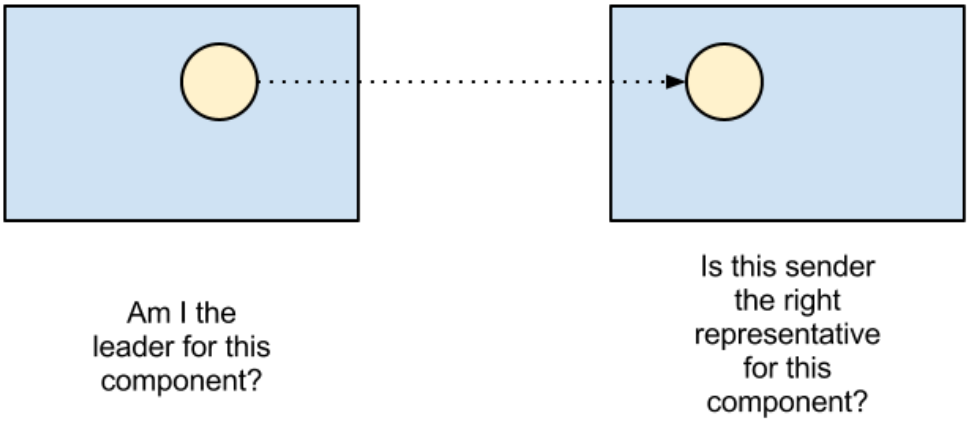
As illustrated in 4.9.4, the premise of a link between components rely on both end's agreement. If either one of them disagree, then the link is not valid.

When a leader of a component failed, the elected new leader will have to update everyone's link table so they all are in consensus of who is currently the representative for this component. The result of the protocol affects the lower layer of the link table, so all nodes in the network affiliated with a particular component could be assure that they are not sending messages to nodes that doesn't exist or listening for messages from nodes that are not in charge of sending the sensor values.

Controller agent

We have described a part of the system that does membership, fault detection. However with only those parts the system, they do not form a fault tolerant system. Without a controller making a right decision at the right time, to synchronize group states, groups will not have consensus and will not be able to proceed as a whole **??**. Controller's responsibilities range from responding to failure events, synchronizing states to group

Figure 4.3: Link table switching



members and connected nodes to ensure the application could still operate.

Reactions and actions tables are set up during deployment. Controller will be mainly handling events and handle according to the rules defined in the tables.

Member ranking Most other work on failure recovery relies on leader election to elect a new leader when the old leader failed which is followed by a group multicast to ensure group state is synchronized to all members.

However, leader election is not necessary if a full member ranking could be determined. Member ranking serves as a lookup table to successor to any node if it happens to fail, also used to recover heartbeat network.

Responding to failure **??** describes the dynamics between agents when a failure has been detected.

When a member detected a failure from other member, the membership agent on the member node will notify local controller agent of this event.

By default, controller agent will notify the leader of the group if it is not, the leader's controller agent will initiate synchronization protocol to synchronize members' membership list.

If the leader failed, the controller agent of the monitoring node will initiate the leader election protocol and become a new leader itself.

Leader election When there is no clear ranking among members, a leader election could provide a mechanism for determine the successor of a failed node.

Recover from failure *Membership synchronization*

Some actions will be syncing membership list across all members for a particular group. This protocol is triggered either by the reaction table above or by explicit request from other agents, such as the Membership agent. Controller agent will access the current membership table and instruct Synchronization agent to start the membership list synchronization.

Link table synchronization

Once the fault has been confirmed and has shunned the faulty node from the network, GMS coordinator will be responsible for propagating this event to other groups in the system that has subscribe to this event.

Let's say that a group has a simple one hop star topology, so all nodes will transmit its data to the group leader, when the group leader has been reported to be partitioned away

from the network or failed, then what will happen is that each group member will elect a new leader by some heuristics, since it has the link table for the previous group leader, it will know which node it is suppose to link to outside the group upstream, and change its local link table accordingly, the new leader will determine the new linking table of its members by consulting the group policy, send a multicast to the group to route all their data to the new leader. The upstream node should either be inside a group managed by the GMS, or a Master assigned gateway, it should also receive this update according to the group policy which GMS will also inform them of.

Essentially, GMS is global in the network and will have full knowledge of the group policy for all groups in the application, and it can follow the group policy to propagation fault events to the appropriate groups.

False positive fault detection

It appears to be possible to have false positive fault detection when a node is not dead but actually got partitioned away from the network for a short period of time. If it is the leader that got partitioned away for too long, several members will be detecting this failure and they might all initiate a leader election. Since they all know of this situation, every node detecting a failure will wait for a random amount of time before sending the message. If a leader election message has been received, it will terminate its current action and continue to the second phase of the leader election process.

However, it is possible that leader is not actually dead, and it is also monitoring the members. The leader might conclude that the members are all gone and will also generate a failure event (since there is no one to synchronize to). This is a split brain problem because the remaining members will elect a new leader and proceed in synchronizing the link table in neighbor nodes, but the old leader is still operating and sending data between

the neighbor nodes, this will create a conflict both in the group and cause a confusion among the outsiders.

Assuming both partitions can talk to the neighbor nodes with objects connected to their objects, there is no way for the partitions to detect the problem within themselves but only the outsiders.

The outsiders, whose objects are connected to the group, will be the fault detector and will notify both leaders of their existence along with their scoring. The leader with less scoring will give up their leadership, and try to merge with the other partition if possible. If it is still not possible after a timeout, it will try to notify the Master of this situation.

Daisy chaining

Since it is also possible that heartbeat is in daisy chain that the any node only monitors one node at a time, and no two nodes monitor the same node. When that happens it is still possible that leader could partition away from the system and appear again later in time. Since the new leader is the one monitoring the old leader, when the old leader resume and start sending heartbeat, the new leader could be sending a reconfiguration message to Master, or if it is not severe enough to do a full reconfiguration, it could resign by sending the old leader a resign message to inform the leader to reconfigure its connected objects about this change of leadership, and it will resume to become a normal member again.

The message complexity for the operation of resignation should be O(2+2H(m)) where H is a function that returns the number of nodes hosting connected objects m.

Misc. need review

Reaction table Similar to a routing table, Controller agent will also have a table to look up which actions it could take given a certain type of failure event.

Source	Detector	Event	Action id
“all members”	“any member”	no heartbeat	0
“all members”	“any leader”	no heartbeat	0
“leader”	“any member”	no heartbeat	4

Table 4.1: An example of reaction table

Action table This table list all actions that a controller could do. This table follow similar style described in the work of ADAE with rules that provides graceful degradation for most actions.

Id	Profile type	Next	Secondary	Doer	Receiver	Fun
0	standard	3	1	“leader”	“all members”	“me
1	secondary			“leader”	“operating members”	“me
2	standard			“any member”	“leader”	“ser
3	standard			“leader”	“all members and connected nodes”	“lin
4	standard			“operating members”	“operating members”	“lea

Table 4.2: An example of action table

When a standard action failed, the secondary action will be triggered, for example, if action 0 failed, action 1 will take over since it is a secondary of action 0. When action 0 finish execution, action 3 will follow it immediately since it is a next of action 0.

Event queue Controller will be bombarded by lots of events coming from multiple sources in a short period of time, to ensure all events are stored in chronological or importance order, a event queue is used. Any event that other agents send to notify controller will be stored in this queue.

Event queue synchronization

It is very likely that if nodes failed, the events carried on the nodes will never see the light of day in other nodes, and will never be handled. To prevent missing events,

Event name	Priority
“No heartbeat”	0
“Event queue synchronization”	1

Table 4.3: Event queue

controller will have to synchronize event queue among members.

Preemptive event queue

Some events have higher priority, and those events should come in in sparse intervals. Event queue synchronization is an important event that any controller should preempted before other unhandled events.

Chapter 5

Experimental Design and Result

5.1 Experimental Setup

5.1.1 Sensor Nodes

5.1.2 Fault Tolerant Policy for FBP

Chapter 6

Conclusion

dkljfa;lkfj; sd;lkf j

6.1 Summary of Contribution

Chapter 7

Future Work

7.1 Group connection types

7.2 Mapping

Q: Inclusion problem, how to solve it? How severe it is?

A: The problem is due to the low redundancy level of a compoennt which is mapped to a node with other compoennts which have higher redundancy levels. This problem does not always have a solution, it depends highly upon the resources in the network, it is unavoidable. However, we are considering possible solutions to address this problem in the future by making sure the mapping results does not have this pattern and could generate possible solutions to solve this problem by either increase the redundancy level of the vulnerable component or purposefully avoid mapping to dangerous nodes that would put the component to risk.

But the bigger question is, if compoent FT policy is enough to ensure application durability, at the current state, if any component does not have minimum redundancy

level of 2, that application is in the risk of single point of fialure, there would be needed a way to inspect whether the policy is fault tolerance at the application level, or introducing several application level FT policy and that is something that we could be looking into in our next research work.

7.3 Policy

When application are getting complex full with features and configurations, it is important to have a high level declarative configuration policy language to specify the control for features and control of their respective behaviors smoothly. I propose a high level policy for fault tolerance that could be translated to low level application requirements.

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