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初稿

蘇適撰



# 國立臺灣大學碩士學位論文 口試委員會審定書

初稿

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 then we introduce the reconfigurable fault tolerance system problem and approaches to solving this problem. Next, we describe some related work. Lastly, we present our proposed solution to this problem.

### 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 environment in its proximity. Wireless sensor networks are typically employed in a variety of applications ranging from home automation to military.

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-intensive 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][10][2][14][9][12][15][16].

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

## **1.2 Redundancy architecture**

A distributed system usually consists of data services that clients or other services could read or write with some associated communication frequencies according to the application requirements. The problem of partial failures makes service redundancy a fundamental technique to distributed systems as it improves availability, eliminates single points of failure. A system that is hardwired to get data from node X will fail when X fails. The problem of designing a system with replicas where node Y, which can provide the same service, can take over when X fails. To design such system it is important to have models or definitions of a service such that it could be replicated onto different hosts with different specifications. It is also essential that the system could have some data structures or framework to track and manage available resources in the network. Autonomy is an important attributes of distributed systems since most of them would be left unattended for a long period of time, it should be able to recover, reconfigure itself in the event of failure.

## **1.3 Problem Definition**

The problem of designing a distributed system that could handle failures and increase availability for all services is different depending on the system and application requirements. But some generalities can be established. There will usually be a set of components which will be assigned to a set of hosts, and some components are associated with some communication frequencies and are reading/writing data from other components. However hosts could fail, and there is a time constraints on the recovery process. The objective of this system is to detect and handle failures with technique such as reconfiguration with minimum communication and memory overhead.

In thie thesis, the problem of reconfigurable fault tolerant system on WuKong of component based architecture is considered. The problem is interesting and worth solving by itself as this problem existed in all kinds of distributed systems.

### **1.3.1 WuKong: Intelligent Middleware for Flexible Sensor Configurations in M2M Systems**

WuKong: Intelligent Middleware for Flexible Sensor Configurations in M2M Systems [11] consists of frameworks that supports flexible configurations of application specifications from flow-based programming. It uses component based architecture where services could be represented by software components which will be deployed to a set of hosts, and each host could hold more than one component.

### **1.3.2 Challenges**

Most existing work treat the problem as a consensus problem where, based on the terminologies from Leslie Lamport on his paper Paxos [4] where acceptors will come to a consensus for the value of a particular variable. And so the ordering properties is really important among the acceptors so none of them could reach a different state. However distributed systems have some unique properties that makes this problem really hard is that communication between nodes are not reliable and the ordering of the messages received could be out of order or dropped.

Typically distributed systems such as wireless sensor networks have tight resource constraints and usually deploy in large quantity which dooms the thought of storing or maintaining any additional states, resources has to be used economically.

## **1.4 Approach**

This thesis proposed an original approach that hasn't been done before. Previous work on the problems has been considered the use of consensus protocols with some sort of configurations that contain a set of members, and for every failure the configuration will be reconfigured using the said consensus protocol to reach consensus in the system. However, the results haven't shown to work under heterogeneous network with nodes that could carry multiple components. This thesis proposed a novel algorithm with the use of a distributed data structure to maintain the list of members in order that provides a way to track redundancies and recovery from failures when nodes could potentially be both a backup and a service provider, and it also eliminates the needs for messages ordering to reach consensus.



### **1.4.1 Related Work**

The problem of a distributed fault tolerant system has been addressed in many literature [8, 4, 6, 5, 13, 7], however none of the results considered the case of nodes that could carry multiple components and applications with complicated structure with sensors, computation, and actuators. In contrast, most of their assumptions are based on homogeneous network and applications with a few types of services.

## **1.5 Thesis Organization**

Our work overlaps many diverse but interconnected domains, each topic being itself a subject of advanced research and abundant literature. Chapter 1 gives an introduction to the problem and outline of the approach used to solve the problem. The second chapter gives a brief background overview of the topic that this work based on. 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. Then we talked about component model based middleware. The following chapter describe our work in a reconfigurable component based fault tolerance system. In this chapter we give detail description of our method and algorithms, then we present benchmark results to evaluate the performance, correctness of each mechanism followed up with a deployment with an application from WuKong. And finally, chapter 5 presents some conclusions.



# 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 instrumented 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 simplifies 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 adaptable and evolvable for new services in new environments.

Next section presents an instance of a component based middleware.

## **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

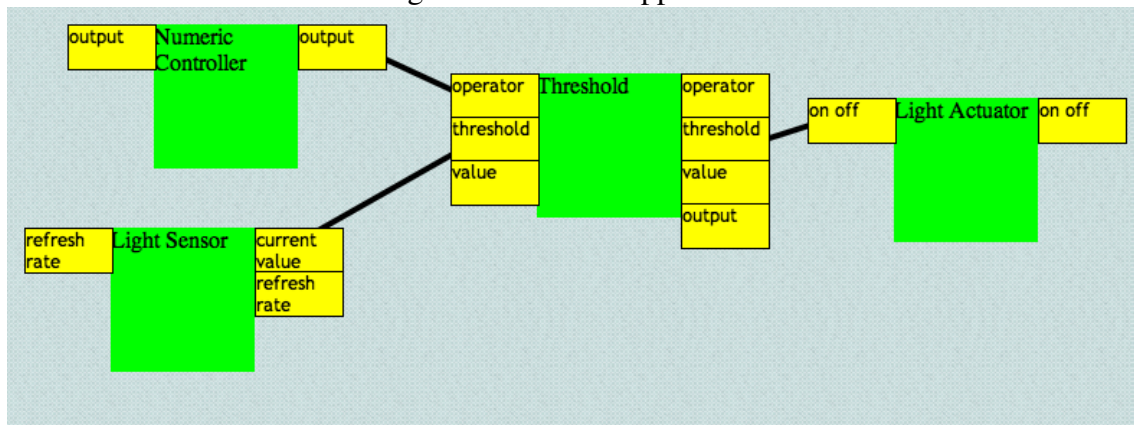
protocols. The hardware has a fixed range of sensors, and the applications cannot be easily ported to other platforms.

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-machine (M2M) applications with ease. The main contribution of this project is to support intelligent mapping from a high-level flow based program (FBP) to self-identified, context-specific sensors in a target environment[11].

### 2.3.2 Flow Based Programming

Figure 2.1: A FBP application



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 components 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 mathematical 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 matching data type. The FBP application 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 desired 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 determined 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 WuObject 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.

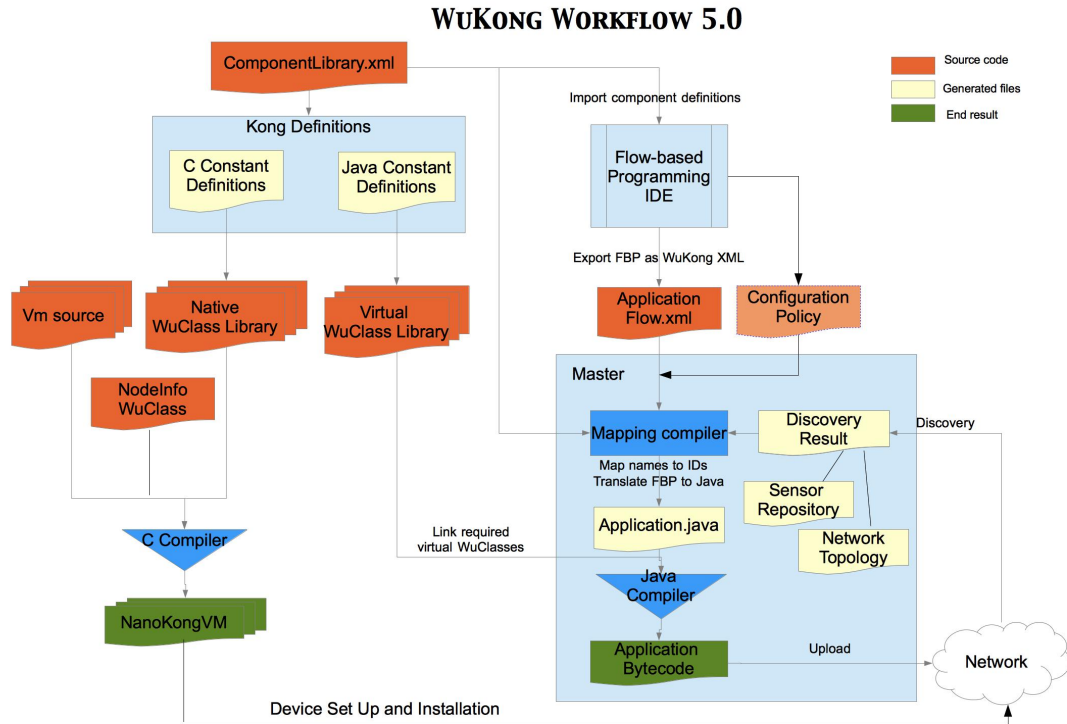
### **2.3.4 Compilation and Mapping**

Figure 2.2 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



Figure 2.2: WuKong application build flow



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 substitute 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.

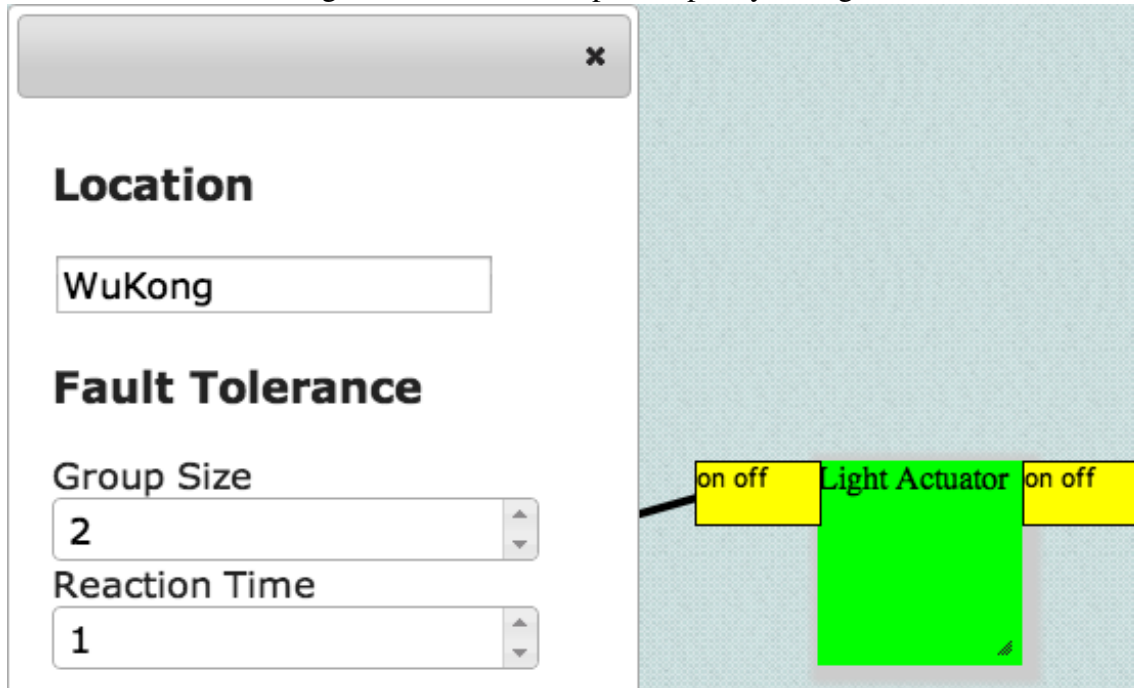
### **2.3.5 System Progression Framework**

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 blueooth 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**

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

Figure 2.3: A user component policy dialog



### 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 environmental influences could break and shut down the devices easily. Fault Tolerance policy enables users to specify relevant policy for tolerating failures in the granular level. This thesis will discuss more on fault tolerance policy in the following chapter.



## Chapter 3

# Reconfigurable Atomic Service for Component Objects

This chapter presents the Reconfigurable Atomic Service for Component Objects, RASCO in short. First the reconfigurable service problem is described in section 3.1 and the profile framework is described in section 3.2. Section 3.3 describes a new replicas configuration models called strips to track and handle replicas dynamically. After that section 3.4, 3.5 and 3.5.1 presents the distributed algorithm used to solve the problem. The models and algorithms are tested extensively on various benchmarks, described in section ??, and the results are discussed and compared with existing fault tolerant system models in section ??

### 3.1 Reconfigurable Redundancy Service System

is a fundamental technique to distributed systems as it improves availability, eliminates single points of failure. A system that is hardwired to get data from node X will fail when X fails. We want to design a system where node Y, which can provide the same service, can take over when X fails.

Reconfigurable Atomic Service for Component Objects (RASCO) is designed to solve

this problem by introducing a new replication model. RASCO allows in situ reconfiguration for maintaining consistency between services and replicas.

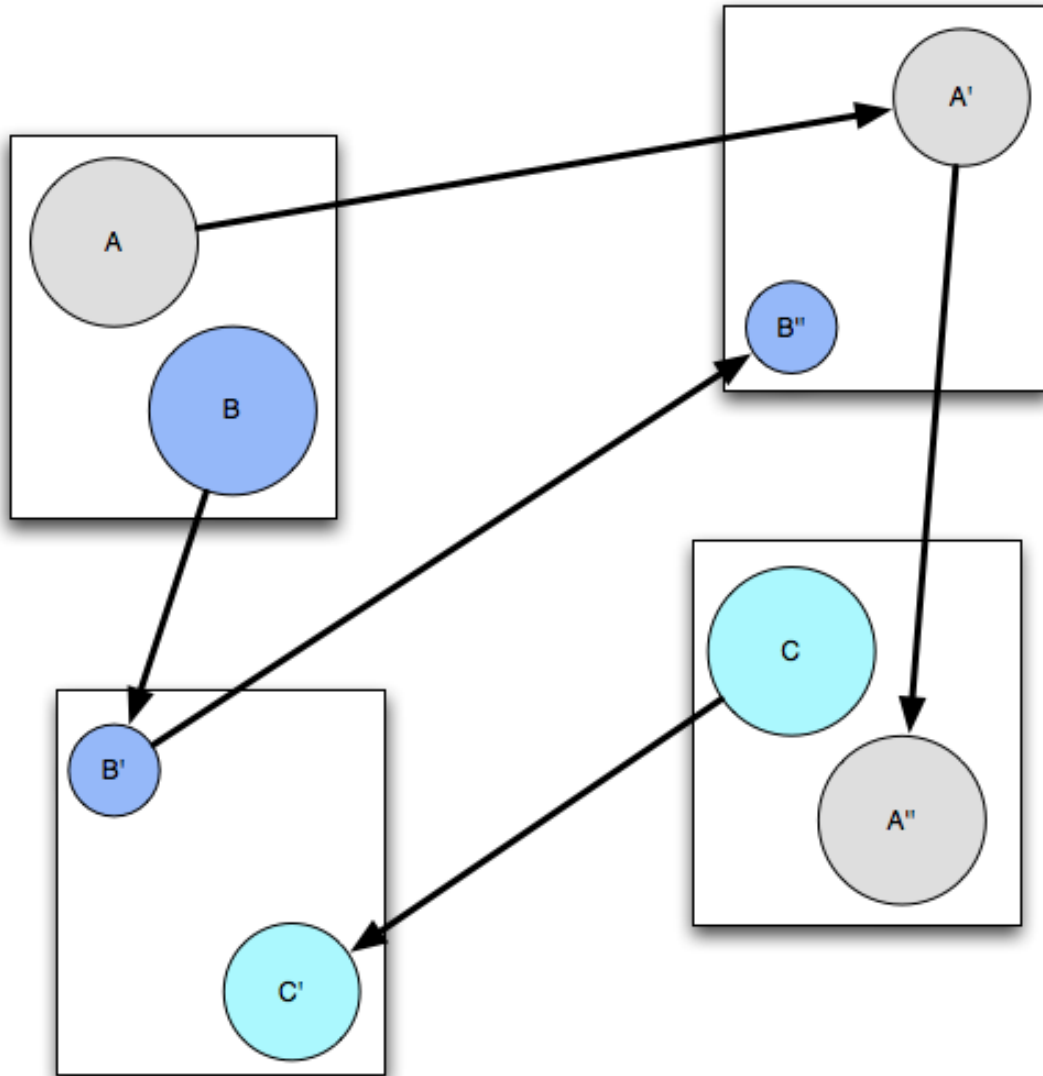
## 3.2 Profile Framework

In this work, we build upon WuKong, a loosely-coupled component based architecture for M2M systems. WuKong uses profile framework to enable the handling of physical resources on heterogeneous sensor nodes, and for higher abstractions of software component capabilities. As future M2M systems could consist of many heterogeneous sensor nodes and actuator nodes, two main concepts in profile framework, namely WuClass and WuObject, was introduced to allow WuKong to track, and manage physical resources in the network. [11] However WuKong has no support for fault tolerance. We proposed a solution to track, manage and maintain consistency among replicas based on concepts from profile framework.

## 3.3 Strips

This work proposed an algorithm that uses strips, each of which consists of service holders prioritized by some metrics to keep track of changes and maintain service availability in the presence of failures. Strips consists of members which are chained together in series to the next that when one member failed, the next one will take over, except the last one. For example, for a strip constructed like this  $\rightarrow 1 - 2 - 3 - 4 - 5$ , when 3 failed 4 will take over the place of 3 and shift all the objects after it forward, and the new chain will look like this:  $\rightarrow 1 - 2 - 4 - 5$ . Now if 1 failed, 2 will take over and members after 2 (including 2) will shift one position forward that would result in  $\rightarrow 2 - 4 - 5$ . Typically the head of the strips is the component in the application, while the rest are replicas.

Figure 3.1: An example network with several strips



In a heterogeneous network, each host could carry more than one WuObjects and could provide more than one service. Since each strip represents a specific component in the application, there will typically be many of these strips present in the network where each of them could crisscross with one and others. It would mean that a node could be a service provider and a replica at the same time.

A node stores membership information of the strips where it is a member of and also the strips of the nodes it is monitoring. Each stripe is stored as a list with membership address information in the same order as the order of the strips so for example, the current head of the strip is the first element of the list. Nodes use the information stored to track and notify the nodes for any changes in the strips.

Figure 3.1 illustrates a network with many strips as strips crisscross and layout in the network. Each block represents a host, and each circle is a component. The name of the component represents the type of the component, and replicas have the same name as the component but with an apostrophe next to it. As shown in the figure, each strip could crisscross and could have replicas residing with another component within the same host.

### **3.4 Decentralized Failure Detection**

The system assumes a fully connected heterogeneous network with sensors and actuators where each node in the network could host multiple components. This work uses heartbeat technique, a popular technique widely used to detect failures in high-availability distributed systems. Each node would send a heartbeat message to its detector periodically in a fixed interval until it's unable to send messages anymore. Each node is therefore suspected dead when it stops sending messages after a period of time.

There are many related work on heartbeat protocols to ensure high-availability whether it uses star topology, or a ring topology; the main purpose for a heartbeat protocol is to detect failure within a network as fast as possible. Our work assumed a ring topology heartbeat protocol such that a node A would send heartbeat to node B and so on, but the last node would send heartbeat back to node A.



## 3.5 Failure Recovery

Several strips would be cut off in the event of failure, and if the failed node carries the component of some strips, the system which hardwire the location of the failed component would not be able to continue to function. Every node needs to have knowledge of the members of the strips of the nodes it is monitoring. For example, if node A is monitoring node B, A would know the members of all strips in node B in addition to its local strips. In this case, the detected node will prepare a update message to inform all members of the strips with which the failed node is associated with. Assuming that every node that monitors other node will have knowledge of the strips that it contains and the members that the strips pertain. The node would send out a marker multicast first to confirm the nodes which are still functioning, and once all acknowledges have been received, it will proceed to send the update message to update their local knowledge of the strips to reach a consensus. The ordering of the messages wouldn't matter since the end state of any failure sequence for any strip would be the same. For example, given a strip of three members  $\rightarrow 1 - 2 - 3$ , if the updated failure sequence is given in any permutation by  $[1, 2]$  or  $[2, 1]$ , the end results would be the same  $\rightarrow 3$  since the remaining members from those two failure sequence is the same and the relative order of the members would stay the same. Therefore there is no need for extra communication overhead to maintain ordering to guarantee level of consistency between members since they will all come to the same conclusion given each receiver receive the same messages.

### 3.5.1 Reconfiguration

Even though consensus of the new configuration for each affected strip has been reached, some nodes with component that acts as a client to another component for data

or the reverse would also have to have consensus on the updated primary holder of each affected component. And the node that is monitoring the node monitored by the dead node would also need to update on its knowledge of its monitored node in order to recover the next possible failure.

RASCO will initiate a reconfiguration service to reconfigure the network to adapt to the new strip configurations. Reconfiguration service is implemented by a distributed algorithm which is initiated by the detected nodes. First the initiator node would have to identify the components that are reading/writing data with the components carried by the dead host. This would be done by requesting the link information between components at the higher level provided by the application. Then each member of the strips of the connected components would be updated with the information about the change in the host of the failed components.

Reconfiguration service has message complexity of  $O(m)$  where  $m$  is the number of strips where its components are linked to the failed components.

## Chapter 4

# Deployment of Reconfigurable Atomic Service for Component Objects

### 4.1 Reconfigurable Atomic Service for Component Object

RASCO allows for continuous and large changes in the underlying network. Providing consistent shared objects in a dynamic network is what RASCO is developed for. RASCO achieves this by introducing the use of strips. Strips enable the system to track, maintain replicas and maintain consistency in the presence of failures. However, the number of failures RASCO can handle is still limited by the number of spare nodes that could provide required services. It is possible after a large change in the network, none of the nodes providing a service is there anymore, so it is impossible for the newly joined nodes to tap in and take over. To handle this large and permanent changes, WuKong supports a system progression framework that could handle such large change in the network with dynamic *reconfiguration*. WuKong reconfiguration reassigns associations between software components and hosts. But it does not have a solution to what the new assignment would look like. This deployment problem is a gap that should be considered.

In the case of RASCO where deployment has to be continuously adjusted, the deployment problem is more of a online problem, so there is a tighter limit on time available to

compute the assignment and strips.

## 4.2 Optimal deployment

The problem of deploying a specific distributed system onto a network structure typically consists of mapping the components of the system onto the hosts of the network. The mapping is subject to constraints. In the case for RASCO, the constraints are whether a node supports certain service to host certain components, and how much communication overhead would induce from the assignment to maintain consistency for the strips, and from the perspective of WuKong, some components need to seaparate from other components to achieve fault tolerance, and some needs to place together to function properly.

Determining such an optimal deployment is a *combinatorial optimization* problem. Combinatorial optimization problems are generally extremely challenging computationally. However, the problem is ubiquitous as it happens all around our lifes, whether it is companies trying to assign limited resources to meet certain objectives, or institutions allocating resources to its staff members to minimize cost, are examples of combinatorial optimization problems. However it is difficult to predict what will and what will not work. It is unlikely that a single approach will be effective on all problems or instances of the same problems.

## **4.3 Set Covering Problem**

### **4.3.1 Greedy Approximation Method**

## **4.4 Hybrid Method**

## **4.5 Discussion**



# **Chapter 5**

## **Conclusion**

### **5.1 Summary of Contribution**

### **5.2 Discussion**

### **5.3 Future Work**

#### **5.3.1 Questions**

Q: How does the system recover from two consecutive failures in the network?

A: We assume a much simpler failure model where there can be at most one failure happen at any point in time. It is a reasonable assumption given that our system recover from failures fairly quickly ( 2 secs) ....

Q: How does an application is being compiled into low level bytecode? And when and how does WuKong reconfigure the nodes?

Q: What happen when an application is deployed? What is specifiially at work?

### 5.3.2 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.



### **5.3.3 Group connection types**

### **5.3.4 Mapping**

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

A: The problem is due to the low redundancy level of a component which is mapped to a node with other components 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 component 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 failure, 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.

### **5.3.5 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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