A Decentralized Multi-agent Service Lookup Mechanism: Cooperation and Communication without Center Agents in RoboCup Rescue

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Abstract

Multi-agent systems (MAS) offer promising solutions to complex problems in distributed, open environments. Each MAS agent uses limited resources, incomplete knowledge, and limited capabilities to contribute to the solution of complex problems via agent interactions. For this reason, how to perform efficient searches for compatible agents is currently an important research topic. The author describes a proposed decentralized service lookup (DSL) mechanism that constructs service directories that are distributed among agents, who use keywords to find resources, capabilities, and knowledge held by other agents. The proposed DSL avoids three common problems in this area: broadcast queries, single point failures, and performance bottlenecks.

1. Introduction

Multi-agent systems (MAS) offer promising solutions to complex problems in distributed, open environments. Each MAS agent uses limited resources, incomplete knowledge, and limited capabilities to solve complex problems via agent interactions. This makes efficient searches for compatible agents an important research topic in Information Science. In this thesis, I will give a detailed description of a decentralized service lookup (DSL) mechanism that prompts agents to use keywords for looking up services provided by other agents. The DSL serves as a means for finding compatible agents for purposes of receiving larger rewards and managing resources, capabilities, and knowledge more efficiently.

MASs consist of agents with limited capabilities and incomplete environmental knowledge; the agents solve problems by interacting with each other within loosely-coupled networks. Currently, computer science researchers tend to solve complex problems in distributed, open environments using systems (e.g., RoboCup Rescue [8]) and architectures (e.g., Open Agent Architecture [10]) that view agents as modular components. Individually, agents in a MAS do not have sufficient information for problem-solving.

Research on agent interaction for increasing rewards can be categorized as a) efficient searches for compatible agents, and b) means for multi-agent operations. In the first category, proposed methods include market-based mechanisms [14], middle agents [3], recommendation and request forwarding [5, 7], coalition formation [13, 2], and center agents [8]. Research in the second category is primarily focused on the communication languages (e.g., KQML [4]) used by agents for expressing their needs after they find compatible agents.

There are at least three important challenges to finding compatible agents. The first is referred to as *broadcast queries*—the means by which agents interact. Since messages are broadcast to all agents in a MAS, this method is considered inefficient because it increases both computing and communication overhead. In Matchmakers [17], RoboCup Rescue [8], and similar programs, middle agents must be able to communicate/interact with all other agents. If this task requires excessive amounts of computation and communication resources, it can lead to the second important challenge, referred to as *performance bottlenecks*. If middle agents fail, then all other MAS agents will not be able to find compatible agents—a situation known as *single point failure*, the third challenge.

The DSL described in this paper avoids these challenges by means of careful information management—that is, by building decentralized service directories. The DSL also provides a keyword system for agents to use when searching for compatible agents. To address the issue of communication efficiency, I will use RoboCup Rescue without center agents as an experimental platform for verifying the proposed DSL's ability to avoid the three challenges.

The outline for the rest of this paper is as follows: in Section 2 I will discuss research on efficient searches for compatible agents and the current literature on broadcast queries, single point failures, and performance bottlenecks. The proposed DSL mechanism is described in Section 3; the description includes an overview, specific information

on the Chord protocol, and DSL operations. In Section 4 I will present the experimental design for testing the proposed DSL and discuss the results of the experiments. A conclusion is offered in Section 5.

2. Related Work

2.1. Middle Agent

Middle agents have different names in different systems. In Open Agent Architecture they are known as *facilitators* [10], in InfoSleuth they are called *brokers* [12], and in RETSINA they are referred to as *matchmakers* [17]. Middle-agent MASs also have provider and requester agents. In a typical interaction, providers send advertisements describing their services and requesters send their service requests to middle agents. The middle agents then return matching advertisements to the requesters. Single point failures and performance bottlenecks occur when all agents in a system send their requests and/or post their advertisements to middle agents within a narrow time frame.The proposed DSL uses a keyword system to manage these interactions.

2.2. Market-based Mechanisms

Another approach makes use of market-based mechanisms to manage agent actions—for instance, bidding for services in auctions using contract net protocols [14]. However, it is still possible for large numbers of agent messages to cause performance bottlenecks, or for unexpected auction breakdowns to cause single point failures.

2.3. Forwarding Recommendations and Requests

In systems based on these two methods, agents send requests to other agents, who either respond with recommendations or forward them to other agents. For example, Iamnitchi and Foster [7] proposed a resource discovery system based on a grid. If A sends a request to B for resource x and B does not have the resource, B uses different request forwarding strategies with C, D, E, etc. until it locates an agent that has the resource. According to an experiment they conducted using different scenarios to test several request-forwarding strategies, the strategy of forwarding requests to agents who have the best track records of satisfying past requests is most successful in environments with unbalanced resource distributions. Forwarding requests to a randomly chosen agent was also identified as a satisfactory strategy, especially when resource distribution is balanced.

2.4. Coalition Formations

In systems based on this method, agents organize coalitions among groups according to agent interests [13, 2]. This allows for quick identification of other agents for interactions based on need. An example is Foner's [5] Yenta Lite system, in which agents use a recommendation system to find other agents who share common interests.

2.5. RoboCup Rescue

RoboCup Rescue [8] is a MAS used to simulate large-scale urban disasters. It utilizes three types of platoon agents and three corresponding types of center agents; these are described in detail in subsection 4.1. A platoon agent must use a corresponding center agent in order to interact with other types of platoon agents. If a center agent fails, its corresponding platoon agents will be blocked from interacting with other types of platoon agents, resulting in a single point failure. Performance bottleneck problems arise if all platoon agents of the same type move to interact with other agent types within a short time frame. As I will show in Section 4, the proposed DSL allows platoon agents of different types to communicate with each other without having to rely on center agents, thus avoiding both of these problems.

2.6. Multiple Middle Agents Architectures

Another strategy for avoiding performance bottlenecks and single point failures is to incorporate multiple middle agents into a MAS architecture. Three examples of this approach are Open Agent Architecture [10], RETSINA [18] and DECAF [6]. In RETSINA, after a matchmaker organizes a list containing the IDs of agents whose capabilities match incoming requests, it uses an *agent name server* (ANS) to find them. RETSINA uses a large number of these servers. An ANS can provide a multicast-based discovery service in order to respond to the needs of dynamic environments, and uses a flexible updating method to map agent names to their locations. The availability of more than one middle agent and ANS to serve the needs of individual agents allows this system to avoid single point failure and performance bottleneck problems.

The discovery service [9] provided by an ANS is built using a multicast-based protocol such as Gnutella (global discovery) or UPnP (local discovery). When an ANS performs a search, it sends a multicast message to an entire network in order to contact all other ANSs; this can result in a broadcast query problem.By avoiding the use of extra agents, the proposed DSL system is better able to respond to changing agent behaviors with much fewer messages being exchanged.

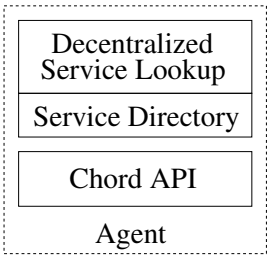

Figure 1. Agent architecture with DSL

3. Decentralized Service Lookup

The agent architecture in the proposed DSL MAS is shown in Figure 1. Using Chord API, agents build and maintain local information in the form of finger tables, successor lists, and service directories. They use DSL operations and local information to locate services and to find agents that provide them.

3.1. Chord Protocol and Chord API

The Chord protocol addresses object location problems using a peer-to-peer network environment without centralized or hierarchical control organizations. Chord supports one simple operation, expressed as "given a key, Chord maps the key onto a node" [15]. Assuming n number of nodes, Chord protocol takes $O(\log(n))$ messages to look up the location of a key with $O(\log(n))$ nodes, with each node having $O(\log(n))$ amount of information stored in it. Chord protocol maintains information even when nodes join and leave the system; at a high level of probability, each event results in no more than $O(\log^2(n))$ messages. The Chord protocol uses load-balanced, decentralized, scalable, and flexible naming properties, all of which are common characteristics of large-scale, dynamic, and open peer-to-peer environments. Other decentralized protocols that have been suggested for locating objects in peer-to-peer systems include Pastry, Tapestry, and Freenet. Chord is considered more simple and reliable [15].

Chord's key-mapping feature provides a method for MAS agents to build decentralized service directories in the absence of global information or centralized control. Chord defines the means for a) locating a key, b) finding new nodes to enter a system, and c) handling and recovering local node information if an agent fails unexpectedly.

3.1.1. Consistent Hashing

Using a hash function (e.g., SHA), Chord assigns an ID to each node and assigns a key to each object; in both cases, the range is from 0 to $2^m - 1$ (m is the length of ID or key).

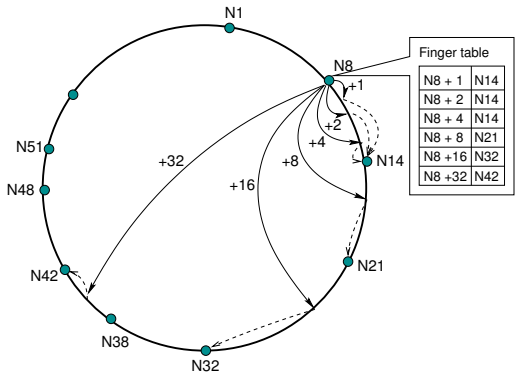

Figure 2. Finger table in Chord protocol

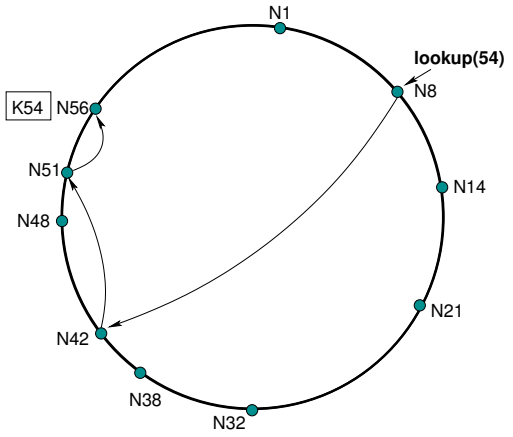

Figure 3. Key lookup with finger table in Chord protocol

Chord also organizes system nodes into Chord rings. X is said to be the successor of Y (either an object or node) if it is next to Y in clockwise order in a Chord ring.

3.1.2. Scalable Key Location

Chord ring nodes maintain their successors' locations as part of their local information. The nodes also maintain finger tables that contain m entries. The i^{th} entry in the finger table of node X (called the i^{th} finger of X) stores the successor of $(x + 2^{i-1})$, where $1 \leq i \leq m$. The complete finger table of a node (named node 8) is presented in Figure 2. This scheme has two characteristics: a) each node only stores information on a small number of other nodes, and b) the information stored in one node is insufficient for finding a key's successor. In other words, finding a key's successor requires several steps involving several nodes.

In Figure 3, for instance, node 8 wants to look up an

Service Keyword	Agent's Location
"gcd"	"140.113.88.55"

Figure 4. Service directory

object with key 54. First, node 8 searches its finger table and learns that it must contact node 42. According to its local information, it knows that node 52 is node 42's successor. Then node 42 addresses node 56 by finding key 54's successor in its local information. Finally, key 54 is located as part of node 56's local information. This operation takes $O(\log(n))$ steps involving $O(\log(n))$ nodes. Detailed proofs and pseudo codes are presented in [15, 16].

3.1.3. Dynamic Operations and Failures

In dynamic and open network environments, Chord has two responsibilities: a) maintaining correct local information when nodes join, leave, or fail unexpectedly; and b) ensuring that finger tables and node successors are updated by periodically calling the *stabilize* and *fix_fingers* functions of Chord API. Furthermore, nodes maintain successor lists of size r in order to store their first r successors, thus ensuring that Chord will succeed even if r successors fail. However, if a node fails with probability p, the probability that r successors will fail at the same time is only p^r.

3.2 Agent Local Information

The proposed DSL provides a method for MAS agents to look up services using local information instead of a combination of global information and centralized control. As part of their local information, agents store a) Chord-required finger tables and successor lists and b) service directories (Fig. 4) that maintain service-location pairs using the format <*service keyword, agent's name*>. Service keywords can be defined as names, descriptions, or any other parameter as determined by the application.

3.3. Decentralized Service Lookup (DSL) Operations

3.3.1. Join Operation

Initially, a MAS agent must call a join operation in order to become part of a Chord ring. The join operation triggers the construction of an agent's local information and updates the appropriate Chord ring. As a join operation parameter, the agent must then pass another agent that is already in the Chord ring. The join operation also performs the *stabilize*, *fix_fingers*, and *check_predecessor* functions of Chord API before building the Chord-required finger tables and successor lists. Join operation steps for agent a_1 with service key s_1 and a second agent (a_2) that is already in the Chord ring can be illustrated as

Steps of Join Operation
$a_1.join(a_2)$
$a_1.stabilize()$
$a_1.fix\_fingers()$
$a_1.check\_predecessor()$

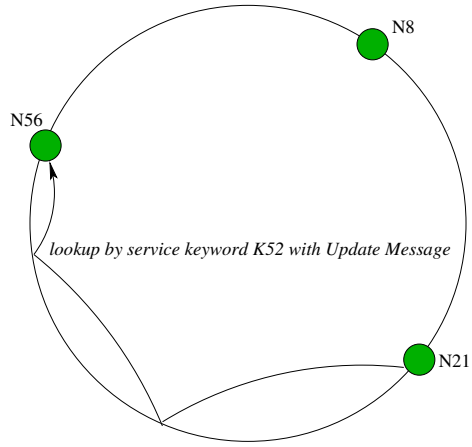

Figure 5. DSL update operation

3.3.2. Update Operation

This operation updates information on the service provided by an agent to the directory. The agent must first identify the service key through consistent hashing, then look for the key in the Chord ring using the Chord API *find_successor* function. The agent finds the key's successor agent, which is responsible for maintaining the service location in its service directory. After the agent locates the key's successor, the agent sends that successor an update message that contains a service directory entry in the format <*service keyword, agent's location*>. After the successor receives the message, it updates the corresponding entry in its service directory.

An example of this operation is presented in Figure 5. In the figure, $N21$ looks for $K52$'s successor using the Chord API *find_successor* function. After several steps, $K52$'s successor—$N56$—receives the update message and updates its service directory.

3.3.3. Lookup Operation

In order to find a specific service, agents must know the service keyword before using the lookup operation to locate the service. This operation returns the service locations

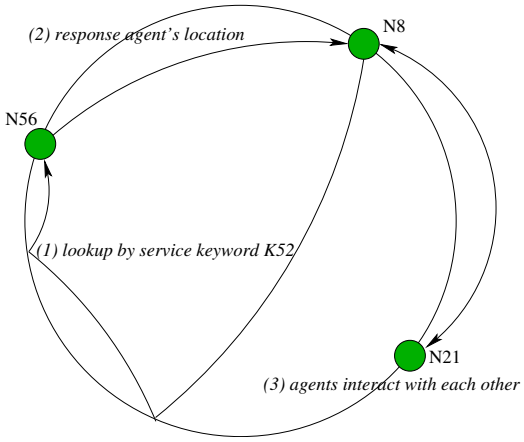

Figure 6. DSL lookup operation

found in the directories of key successors. After receiving these locations, agents interact directly with the agents that provide the services. An example is given in Figure 6. In the example, $N8$ wants to find the agent that provides the service *gcd* with the hash value $K52$. First, the lookup operation calls *find_successor* several times to find $K52$'s successor, $N56$. After querying the service directory of $N56$, the lookup operation returns the location of $N21$ (which provides service *gcd*) to $N8$. $N8$ then interacts directly with $N21$.

3.3.4. Recovery Operation

In a dynamic, open MAS, agents regularly join, leave, and fail. These events often result in outdated local information. The DSL recovery operation helps agents handle these ongoing events. Chord API defines several methods (including *stabilize*, *fix_fingers*, and *check_predecessor*) to recover finger tables and successor lists. The recovery operation also triggers the update operation to update service directories using data from finger tables and successor lists.

4. Experiments and Evaluations

To verify that the proposed DSL helps in the search for compatible agents, an attempt was made to improve the efficiency of platoon agent interactions in RoboCup Rescue without the benefit of center agents. Experimental results (e.g., fire spreading, message distribution, hops for finding successors) were analyzed in order to prove that the DSL avoids broadcast queries, single point failures, and performance bottlenecks.

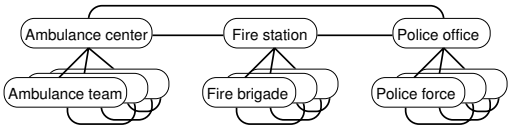

Figure 7. RoboCup Rescue telecommunication

4.1. RoboCup Rescue

The various agent categories in RoboCup Rescue are shown in Figure 7. Ambulance teams are responsible for rescuing injured civilians in disaster areas, fire crews are responsible for extinguishing fires, and police units are responsible for clearing roads that are blocked by collapsed buildings. These three agent types come under the category of *platoon agents*. They have the ability to interact with each other over long distances using a) *telecommunication* via center agents, or b) in-person *oral communication*. For instance, if a fire crew cannot move through a blocked area, it can orally communicate its needs to any police units within 30 meters. RoboCup Rescue also has three corresponding *center agents*: ambulance centers, fire stations, and police stations. As shown in Figure 7, fire crews located in fire stations must use telecommunications to contact police units located in police stations. The respective stations are responsible for forwarding information from individual units in the field.

The main task of fire crews—extinguishing fires—is dependent on two key points: cooperation with and between crews, and the ability to quickly determine where fires or other disasters are occurring. They cannot get to fires or other emergencies if access roads are blocked. In such situations, they must inform police units of the blockages; in other situations, police units must inform fire units of the locations of burning buildings. If fire crews and police units are limited to oral communications, then the efficiency of firefighting crews will be severely restricted. In subsections 4.3 and 4.4 I will describe simulations of these types of scenarios using RoboCup Rescue with and without center agents.

4.2. Rescue without Center Agents using DSL

Without the benefit of center agents, platoon agents in RoboCup Rescue are only able to telecommunicate with other platoon agents of the same type; in contrast, they can use oral communication with all types of platoon agents. Oral communication is limited to platoon agents who are within 30 meters of each other. For example, if fire crew B and police units C and D are within 30 meters of fire

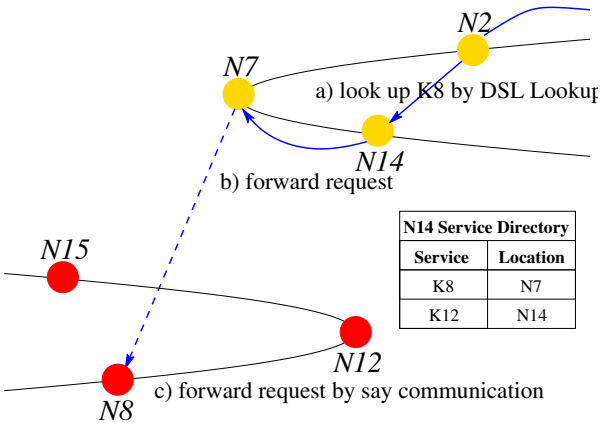

Figure 8. DSL lookup operation in RoboCup Rescue

crew A, then any communication sent by A will be immediately received by B, C, and D. In the real world, this is a very unusual situation. In order to facilitate communication between platoon agents of different types within 30 meters of each other, the proposed DSL system creates directories for service sharing—meaning that platoon agents of different types can interact without having to go through center agents.

In the example presented as Figure 8,

1. Platoon agents of the same type are organized into a Chord ring by a join operation.
2. Fire crew $N1$ (not in the figure) needs help from police unit $N8$, whose service is represented by key $K8$.
3. $N1$ looks for $K8$'s successor via the lookup operation and learns that the successor is $N14$ (Fig. 8 (a)).
4. $N14$ queries its service directory and learns that agent $N7$ provides service $K8$.
5. $N14$ forwards a request to $N7$ (Fig. 8 (b)).
6. $N7$ receives the request and performs the service for $N1$—that is, it forwards the request to $N8$ via oral communication (Fig. 8 (c)).

4.3. Scenario Design

Morimoto [11] developed a Java API named Yab API to help speed up the process of designing agent AIs in RoboCup Rescue. Ako [1] et al. used it to design an agent AI named YowAI that won second place in the 2003 RoboCup Rescue Contest. These YowAI agents were used in the experiments described in this subsection.

Table 1. Number of agents in different scenarios

	Police Office	Fire Station	Police Force	Fire Brigade
YowAI with center agents	1	1	10	10
YowAI without center agents	0	0	10	10
YowAI+DSL without center agents	0	0	10	10

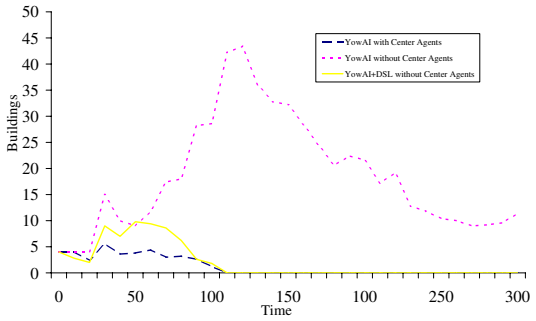

Figure 9. Number of burning buildings in the three scenarios

Three RoboCup Rescue scenarios were designed using different conditions; ambulance teams and the ambulance center were deleted for purposes of simplification and to enhance the focus on interactions between fire crews and police units.The scenarios used the default configuration of RoboCup Rescue: a Kobe City location with four initial burning buildings, a 300-second simulation period, and the number of agents shown in Table 1. The three scenarios were as follows:

YowAI with center agents showing a normal (i.e., non-DSL) result and a performance bottleneck problem.

YowAI without center agents showing that single point failures can cause agents to perform their jobs poorly.

YowAI+DSL without center agents showing that the proposed DSL improves agent performance, and highlighting the performance characteristics of the DSL system.

4.4 Results

4.4.1. Spread of Fire

Statistics from a number of burning buildings were used to verify if the fires in the scenarios spread or were extinguished. In each of the three scenarios, four buildings are burning as the simulation starts. The fires spread through

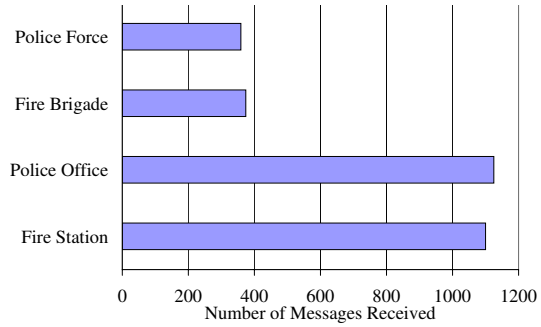

Figure 10. Number of messages received by agents in YowAI with center agents

Figure 11. Number of messages received by police forces

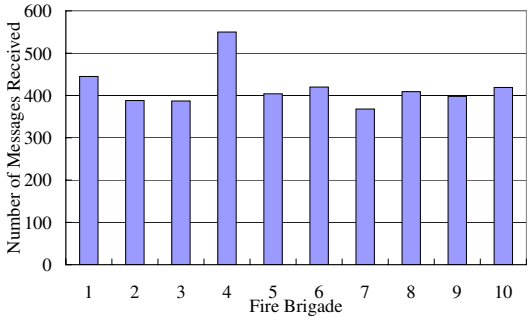

Figure 12. Number of messages received by fire brigades

the buildings very quickly, and become more and more difficult to control. If the fire crews and police units can work together quickly to locate and reach the fires, there is greater potential for extinguishing them before they spread.

The number of burning buildings during single fires in different scenarios (average numbers of simulations$= 5$) are shown in Figure 9. In the YowAI scenario with center agents, the number of burning buildings$= 4$; the fire is completely extinguished by the end of the 100-second simulation. In the YowAI scenario without center agents, the fire crews are not able to extinguish the fire quickly, and it spreads through more than 40 buildings by the time the simulation ends at 300 seconds. This result is due to a single point failure problem, since different types of platoon agents could not interact with each other without the assistance of center agents.

Finally, in the YowAI+DSL scenario without center agents, the fire crews extinguish the fire in 100 seconds, after it spreads through only 10 buildings. The proposed DSL system apparently offers an efficient way for different types of platoon agents to find each other and achieve a common goal without having to address a single point failure problem.

4.4.2. Message Distribution

A comparison was made between messages received by agents in the YowAI scenario with center agents and the YowAI+DSL scenario without center agents to analyze bottleneck problems and the load balance property of the proposed DSL system. As shown in Figure 10, in the YowAI scenario with center agents, the number of messages received by platoon agents (359 by police units and 374 by firefighting crews) was much greater than the number of messages received by center agents ($1,125$ police-related messages and $1,100$ firefighter-related messages). According to these results, performance bottleneck problems occurred because the center agents had to handle a much larger number of messages than the platoon agents, thus increasing computation and communication overhead.

In the YowAI+DSL scenario without center agents, the biggest difference in the percentages of messages received by police units (Fig. 11) and firefighters (Fig. 12) was no more than 7 percent. It is therefore suggested that the reduced number of bottleneck problems associated with the proposed DSL is due to its balanced load characteristic.

4.4.3. Hops of Finding Successors

The term *hops for finding successors* refers to the number of messages that are used to look up a service location by its keyword. The term can be used to discuss system efficiency—that is, the fewer the number of messages, the fewer the number of agents involved, the less time required, and the more efficient the system. The proposed DSL system maps the hash values of service keywords onto a Chord ring agent. After five simulations, the average number of hops was 2.63 over $2,176$ lookup operations. In the YowAI scenario with center agents, 3 messages are required for a platoon agent to send a request to another type of platoon agent. In comparison, the DSL system requires 2.63 mes-

sages to look up a service location, plus one oral communication message and one telecommunication message to forward the request—in other words, it needs 4.63 messages for a platoon agent to send a request to another type of platoon agent within a 10-agent Chord ring. As the number of agents grows, the number of required hops increases at a rate of $\log(number\ of\ agents)$. The DSL system requires $O(\log(number\ of\ one\ type\ platoon\ agents))$ hops for a platoon agent to look up a service location. The proposed DSL system thus uses more messages, but avoids the problems that are associated with a system that uses center agents, and is therefore considered more efficient.

5. Conclusion

The proposed DSL system allows for a decentralized method of service lookup in a MAS by building service directories that are distributed among agents. The system offers an efficient lookup operation for one agent to find compatible agents for service provision and goal-oriented interactions. Most importantly, the proposed DSL system avoids three problems that are very common in systems designed to bring together compatible agents: broadcast queries, performance bottlenecks, and single point failures. By simulating three firefighting scenarios with RoboCup Rescue, it was possible to show that the DSL system can avoid the single point failures and performance bottlenecks that are associated with the use of center agents.

Data on message distribution in the three scenarios shows that the proposed DSL system is capable of balancing message loads and improving interaction efficiency among different types of platoon agents without the use of center agents, while avoiding single point failures and performance bottlenecks. Each DSL operation requires only a few messages among a small number of agents—a significant improvement over the broadcast query method used by other systems. In addition, the proposed DSL system has a recovery operation feature for handling changing behaviors and situations associated with agents joining, leaving, or failing in a scenario. The proposed system is built on a Chord protocol that makes use of peer-to-peer methodology—in other words, no agent is considered more important than others in a Chord ring. The DSL system described in this paper is clearly decentralized.

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