Supporting Groupware Communication with Topology-enhanced Content-based Network

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***Abstract*—Content-based communication is a novel communication paradigm that enables users to communicate with others based on message's content, instead of message's address. Groupware is a kind of software that supports coordination between individual users. An important feature of groupware is that the communication between the specified users is at a high frequency, which is determined by the applied coordination mechanism. Efficient communication in a groupware can support effective coordination between the users. This paper presents a topology-enhanced content-based network, which combines content-based communication with the topology between groupware users, to support content-based communication in groupware. We give a predicate-based method to define cooperation topology, which can effectively describe the topology between groupware users. We also propose a multi-level index structure to support efficient matching of cooperation topology in the forwarding mechanism of the proposed network. We implement the basic feature of our network and evaluate the prototype in a motivating scenario consisting of several coordination tasks. The results show that our method improves the message forwarding efficiency of 1 to 2 magnitude orders.**

***Keywords*—content-based network, groupware, coordination, topology**

I. Introduction

Recently, a novel communication service, content-based communication, rises and draws a lot of interests in various communities [4], [7], [11], [14], [16]. In content-based communication, the flow of a message from its sender to its receiver is driven by the message's content, instead of the message's destination address [5]. A killer application of content-based communication is groupware [10]. Groupware is a kind of software that supports coordination between individual users, including sharing information between users, and coordinating the activities of users. Content-based communication decouples communication from users' identifications. As a result, groupware users can cooperate with others without exposing their detailed identifications to other users.

A limitation of content-based communication is its poor efficiency in forwarding messages. In order to determine the propagation path of a message, the forwarding mechanism of contend-based communication has to match the content declared by the message with the stored user-declared content. Since groupware users may declare various kinds of content, including user's personal information, the environment information, and social network information, matching message-declared content with user-declared content is extremely time-consuming. Considering that a coordination mechanism in groupware usually consists of several rounds of message exchanging, the less efficiency of message forwarding leads to a long responding time of the supported coordination task, which finally restrict the usability of the groupware.

In the context of groupware, we should explore the features of communication between groupware users in order to improve the efficiency of message forwarding in groupware. One of these features is that individual user needs to interact with other users at a high frequency. Another feature is that groupware users usually form a topology in logic. When a groupware uses a coordination mechanism, the topology between users is important in supporting coordination [10], and the interaction between users is carried out by the frequent message exchanging along with the topology. We use the term *cooperation topology* to describe the topology between groupware users. It is a logical topology between the groupware users during a coordination task. Existing works on content-based communication seldom make use of the topology. This kind of works can be summarized as topology-blind content-based communication, which is opposite to topology-enhanced content-based communication proposed in this paper.

We present a topology-enhanced content-based network that combines content-based communication with the topology between groupware users. Generally. we extend the meaning of "content" in existing content-based communication. In our approach, content not only expresses local information of individual users, but also describes the relationship between specified users. We call this relationship *cooperation topology* in this paper. We also propose a multi-level index structure, which is established according to cooperation topology, to forward messages efficiently. Our network is a multi-level overlay network. A content-based network is built as an application-level overlay based on address-based network. The cooperation topology is built as an overlay topology of communication participates based on the content-based network. We evaluate our approach using a collection of simulated coordination tasks. The results show that our network can forward messages efficiently, improving the performance at both node level and network level with little overhead.

The contribution of the paper is as follows:

- We propose a content-based network which introduces cooperation topology. The network is a new kind of communication service supporting the communication in a groupware. We define cooperation topology and use it to improve the efficiency of message forwarding.
- We give a predicate-based method to describe the content, including the local information of individual users and the relationship between individual users.
- We design a multi-level index structure to support

cooperation topology, which aims to improve the efficiency of message forwarding.

II. Motivation and Related Works

A. Related Works

Content-based communication can be regarded as an application-level overlay consisting of client nodes and router nodes, connected by communication links [5]. In content-based communication, message forwarding is based on the content of a message rather than the address. To determine the propagation path of a message, we have to match the message-declared content with the stored user-declared content. This content matching process leads to the poor efficiency of content-based communication [4].

Many works focus on improving the forwarding efficiency of content-based communication. Carzaniga et al. [3], and Jacobson et al. [8] use index-based filtering method to locate the appropriate next-hoop on each node for messages. In [7], Diao et al. propose a XML filtering engine to decide the direction of content-based messages. Both Anirban et al. [12] and Olga et al. [14] use predefined tree topology to determine the optimal propagation path of messages. These works concentrate on how to forward a single message faster. The relationship between content-based messages is neglected. When communication between certain users is frequent, especially in the context of groupware, we cannot simply ignore such a relationship. The relationship between content-based messages actually reflects the relationship between communication participators. Using it, we can improve the forwarding efficiency of content-based communication, comparing with traditional topology-blind content-based communication.

Some works also use the relationship between messages to assist content-based communication. In a parameter based pub/sub model [9], participators can declare the relationship between the exchanged messages. In [1], the authors use the geographic information to build up the relationship between messages generated in specified areas. In these works, the relationship between messages is declared as user-declared content. In our work, we declare the relationship between messages as message-declared content. As a result, different communication tasks can define different relationships in order to support the forwarding of specified messages.

B. A Motivating Scenario

We consider a conference assistant as a motivating scenario to demonstrate the topology between groupware users. The assistant provides two functions. Firstly, it supports users to cooperatively determine the schedule of a conference, including the conference time and location. Secondly, once the schedule is decided, the assistant supports users to book flight coordinately. Users can declare their preferences on the conference, as well as the flight. Users with the similar preference coordinate with others to make the decision on the conference schedule or the flight, supported by the groupware that provides coordination mechanism on demand.

No matter when the user is determining the conference schedule or booking a flight, one single message is not enough. The users have to exchange messages for several rounds in order to achieve coordination. On the other hand, the users do not exchange messages with arbitrary users. During a coordination process, a user always exchange messages with the users who declare certain preferences. When the groupware is performing a coordination process, users who have the similar preference are actually related to each other. We call such relationships the topology between users.

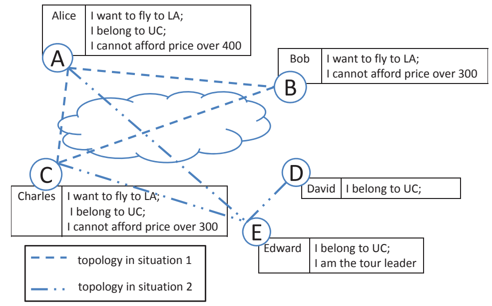


Fig. 1. Topology among Users in the Motivating Scenario

We further investigate how the topology forms between users in coordinated flight booking. Coordinated flight booking is performed within a group of users who share the similar preferences on the flight's destination, airline, budget, etc. We consider two concrete flight booking situations. In the first situation, users hope to form a group with others who head for the same destination. The users determine a flight that is acceptable for all of the group members, and buy the tickets in group-buying manner. In the second situation, users who come from the same unit hope to form a group.

Figure 1 gives an example of five users in coordinated flight booking. In the first situation, the coordination process involves users whose preferences include "*fly to LA*" and "*cannot afford price more than 300*" (Alice, Bob and Charles). In the second situation, the coordination process involves users whose preferences include "*belong to UC*" (Alice, Charles, David and Edward).

Based on the user-declared preference and the applied coordination mechanism, a topology between users is determined. User-declared preference determines the scope of the involved message. The coordination mechanism determines the flow of the involved messages. When a negotiation-based mechanism is used in the first situation, a clique-like topology that covers Alice, Bob and Charles can be founded. When an auction-based mechanism is applied in the second situation, a star-like topology consisting of Alice, Charles, David and Edward appears. The dashed line and dotted-dashed line in Figure 1 show the discussed topologies.

We use such a topology to assist content-based message forwarding in order to improve the efficiency of content-based communication. We provide a predicate-based method that enables message to declare the topology in which they involve. In message-declared content, topology concludes the common part of the content shared by related messages. We store the content matching results for each of the encountered topology. When forwarding message with topology description, we avoid matching the common part of content in such messages. In the communication between groupware users, the common content actually takes up a big percentage of the total message-declared content. By not matching these contents, we boost content-based message forwarding in groupware. Recalling the examples illustrated in Figure 1, the propagation path of the messages in both situation 1 and situation 2 can be directly determined if we know the topology declared by the message. However, in conventional content-based communication, this topology is not explicitly supported. As a result, the forwarding mechanism has to match the corresponding content for each of the involved messages in order to forward these messages.

III. CONTENT-BASED COOPERATION TOPOLOGY

A. *cooperation topology*

We use the term *cooperation topology* to describe the topology between groupware users. It is a logical topology between the groupware users during a coordination task. A cooperation topology is determined by user-declared content and the applied coordination mechanism. User-declared content determines participators of a cooperation topology, and the coordination mechanism determines the topological relationship between the participators. In the following discussion, cooperation topology is referred to as *topology* for short.

A cooperation topology is defined as a combination of *topology patterns*. Three kinds of common patterns are used, *clique topology*, *pos-star topology*, and *neg-star topology*. Each topology pattern is an ordered pair of $\langle S, R\rangle$. S declares the pattern's scope that the users belong to the topology. R declares the pattern's inner topology that the interrelations exist between users. The definition of the three common patterns is as follows:

1) clique topology:
   S : a user set $U\{u_i|u_i$ matches preference $\{p_j\}\}$
   R : a set of directed links$\{\langle u_i, u_j\rangle|u_i, u_j \in U,$
   $u_i \neq u_j\}$
2) pos-star topology:
   S : a user set $U\{u_i|u_i$ matches preference $\{p_j\}\}$
   a user $u' \in U$ matches preference $\{q_k\}$
   where $\{q_k\} \cap \{p_j\} = \emptyset$
   R : a set of directed links$\{\langle u', u_i\rangle|u_i \in U\}$
3) neg-star topology:
   S : a user set $U\{u_i|u_i$ matches preference $\{p_j\}\}$
   a user $u' \in U$ matches preference $\{q_k\}$
   where $\{q_k\} \cap \{p_j\} = \emptyset$
   R : a set of directed links$\{\langle u_i, u'\rangle|u_i \in U\}$

Using the three topology patterns as basic components, complex cooperation topology can be described. In Figure 1, topology 1 (in dashed line) is a cooperation topology consisting of a clique pattern, which covers users who have the preferences "*fly to LA*" and "*no more than 300*". Topology 2 (in dash-dotted line) is a cooperation topology which is a combination of a pos-star topology and a neg-star topology. The pos-star topology consists of the relationships from users who have the preferences "*belong to UC*" and "*tour leader*" to users who only have the preferences "*belong to UC*", and the neg-star topology is the reversal of the pos-star topology.

B. *Content Description Method*

Content is declared by an individual user or a message. User-declared content describes user's preference, current environment information, and user's social relationship. Message-declared content describes the potential receivers of the message. We use a predicate-based method to describe content. A predicate is a tetrad, (**name**, **op**, **val**, **type**), which describes a dependency between content and a target value. **name** indicates the predicate's kind, **op** is a relation operator (for example "=", ">", "<"), **val** shows the target value, and **type** defines the type of **val**. We consider two types of value, numerical (denoted as *int*) and textual (denoted as *string*).

Content consists of a collection of predicates that are connected by logical connectives ($\vee$ and $\wedge$). The predicates connected by $\vee$ (resp. $\wedge$) describe a disjunction (resp. conjunction) of individual predicates. $\vee$ and $\wedge$ can be used together to describe a content expression. In this situation, $\wedge$ has a higher priority than $\vee$. The following content expression describes Alice's preference shown in Figure 1

$(dest, =, LA, string) \wedge (org, =, UC, string) \wedge (price, <, 300, int)$

We use the following expressions to describe the aforementioned topology patterns:

1) $\updownarrow \langle P_i\rangle$ denotes a clique topology.
2) $\uparrow \langle \{Q_i\}, \{P_j\}\rangle$ denotes a pos-star topology, in which $\{Q_i\}$ specifies the center node.
3) $\downarrow \langle \{Q_i\}, \{P_j\}\rangle$ denotes a neg-star topology, in which $\{Q_i\}$ specifies the center node.

Topology patterns connected by $\vee$ and $\wedge$ can describe a cooperation topology in a larger scope. For example, the following content expressions describes topology 2 illustrated in Figure 1:

$$\uparrow \langle \{(pos, =, leader, string)\}, \{(org, =, UC, string)\}\rangle \vee$$

$$\downarrow \langle \{(pos, =, leader, string)\}, \{(org, =, UC, string)\}\rangle$$

IV. TOPOLOGY-ENHANCED CONTENT-BASED NETWORK

A. *Network Structure*

We use a multi-level overlay structure to build the proposed topology-enhanced content-based network. A conventional content-based network runs as an application-level overlay that builds upon an address-based network. Cooperation topology forms higher-level overlays that are built upon the conventional content-based network. Elements of our network include node (**N**), user (**U**) and network link. Nodes are connected through network links. The communication between connected nodes is based on conventional address-based network. Users reside on a node, sending messages to and receiving messages from other users.

A node is capable of processing content expression and forwarding content-based messages in our network. *Interface* is the link between adjacent nodes through which the nodes send and receive messages. When a network initials, each node broadcasts its user-declared content to other nodes. A node receives user-declared content to construct a content-based forwarding table. The table records a mapping between users with specified content and the node's interfaces.

A node forwards a message through matching message-declared content with the user-declared content stored in the forwarding table. For the messages involved in a cooperation topology, a node recognizes the used cooperation topology and establishes a topology index to assist message forwarding. The cooperation topology is indexed and linked directly with the related user-declared content in forwarding table. When a message with the same cooperation topology arrives, the content declared by cooperation topology will be matched directly through the established links with very little cost.

B. *Multi-level-index-based Message Forwarding Mechanism*

To determine message forwarding path efficiently, we propose a cooperation-topology-based multi-level index structure that is illustrated in Figure 2. The index structure consists of two levels. The lower level is *predicate index* which indexes the literal predicates of content expressions stored in forwarding table. Predicate index is used to match topology-blind message-declared content. The upper level is *topology index* which indexes the cooperation topology in encountered messages. Topology index is used to match topology-enhanced message-declared content. If a topology can be matched, the

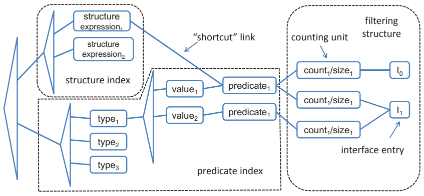


Fig. 2. The Multi-level Index Structure in Forwarding Mechanism

index entry of topology index is linked with the corresponding index entry of predicate index.

Each entry of predicate index is a predicate. We first index the predicates' **name** using a ternary tree. According to the predicates' **type**, we use different index structures to index their **val**. Specifically, we build binary tree for numerical values, and build ternary tree for textual values.

The index entry of topology index is a cooperation topology. The topology is regarded as a sequence of predicates, connectives, and symbols. A system-preserved symbol "@" is used to separate the two parts of predicates in pos-star topology and neg-star topology. We use a modified ternary tree to index such sequences. The tree node is either a literal predicate or a logic connective or a symbol, including ↕", "↑", "↓", and "@". The order of connectives and symbols is defined as "↕" > "↑" > "↓" > "∨" > "∧" > "@". A predicate in a topology is regarded as a string that consists of its four elements. These predicates are compared in alphabetical order.

Once a cooperation topology is indexed, we match the topology with the user-declared content, the predicates, in the forwarding table. If a cooperation topology can be matched, links will be built between the topology and the matched content. These links accelerate the content matching process. The message that declares a topology can use the corresponding links to determine its forwarding interfaces directly.

We use a filtering structure to determine which interface can be matched based on the result of content matching. Filtering structure, which consists of counting units, connects the entries of predicate match index with the interfaces. Each counting unit determines whether an interface can be satisfied by the message-declared content.

Using the infrastructure discussed above, we give a message forwarding process based on the multilevel index structure. When a messages arrives, we match the message-declared content with the stored user-declared content. We first check whether it declares a topology. If the message declares a topology, we then search the encountered topology in the topology index. For the newly recognized topology, we establish the corresponding topology index. After that, we match the content of the topology, and trigger the corresponding counting units. The remaining message-declared content is then matched using predicate index. During content matching, once a counting unit is fulfilled, the processed message is then forwarded through the corresponding interface.

C. Network Execution in the Motivating Scenario

We use the example illustrated in Figure 1 to demonstrate how our topology-enhanced content-based network works. For simplicity, all users are connected with each other by address-based network. We use the first letter of the user's name to denote the node on which the user resides, and assume that the order of node interfaces follows the alphabet order of its neighbor nodes. Here we focus on node **E**. Figure 3 illustrates the forwarding table on **E** after network initialization. In a forwarding table, I_i denotes the ith interface of the node. $p_{i.j}$ denotes the jth piece of content expression on the ith interface. The content declared by a message describes the potential receivers of the message.

Interface	Piece	Content	Interface	Piece	Content
I_1	$p_{1.1}$	(dest, =, LA, string) (org, =, UC, string) (price, <, 400, int)	I_3	$p_{3.1}$	(dest, =, LA, string) (price, <, 300, int)
I_2	$p_{2.1}$	(dest, =, LA, string) (org, =, UC, string) (price, <, 300, int)	I_4	$p_{4.1}$	(org, =, UC, string)

Fig. 3. Forwarding Table on Node **E**

Based on the forwarding table, the corresponding predicate index and the filtering structure are established, which is shown in Figure 4. When **E** receives the messages of the two topologies described in Section II, Figure 5 shows the index structure.

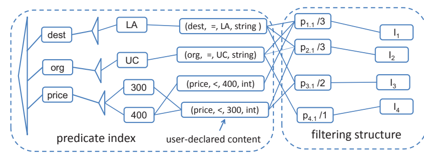


Fig. 4. Predicate Index and Filtering Structure on Node **E**

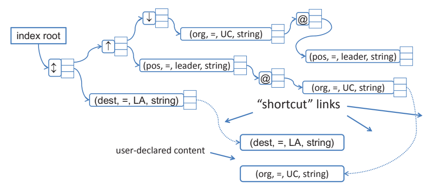


Fig. 5. Topology Index on Node **E**

In our motivating scenario, **E** will encounter messages which declare the neg-star and pos-star topology frequently. Based on the topology-enhanced message forwarding, the propagation path of the messages can be decided quickly: searching the topology index, locating the matched user-declared content (i.e., $(org, =, UC, string)$), and triggering the corresponding interfaces (i.e., I_1, I_3, I_4). If the network is topology-blind, **E** has to match the message-declared content with each item in predicate index in order to forward the same message. In other words, **E** has to match every predicate of the message-declared content using the predicate index for each of the messages that **E** has to forwarded. For the sake of simplicity, we only consider the user-declared content related to the coordination task. However, in real situation, the number of user-declared content is usually very large. Considering the huge different between the number of cooperation topology and user-declared content, topology-enhanced forwarding algorithm saves lots of time in content matching, which finally greatly improve forwarding efficiency.

V. Performance Evaluation

A. Simulation Scenario

We evaluate our network in a simulation setting of the coordinated flight booking scenario. We design four coordination tasks in the scenario and simulate the corresponding coordination tasks based on an implemented prototype. In the following, we briefly introduce the designed coordination tasks:

Task 1 Coordination Group Determination

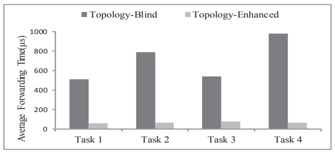


Fig. 6. The Average Forwarding Time per Message(μs)

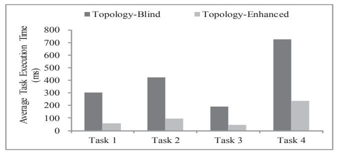


Fig. 7. The Average Task Finishing Time (ms)

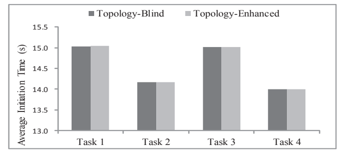


Fig. 8. The Network Initial Time(s)

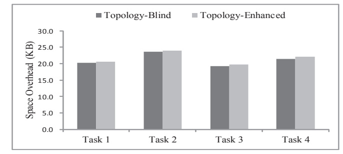
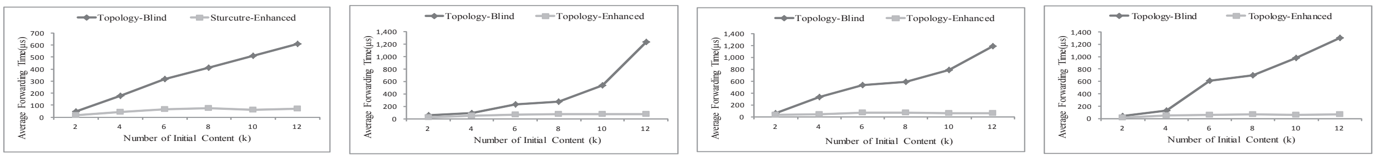
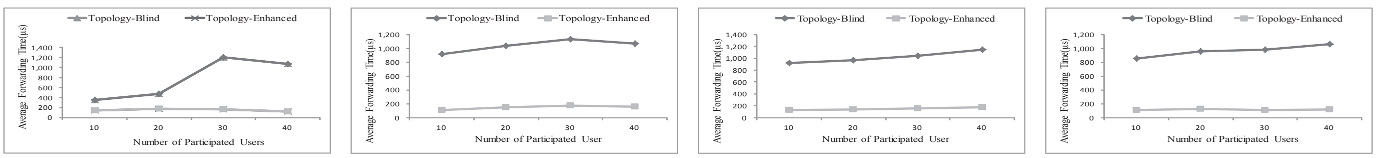


Fig. 9. The Average Index Size(KB)



(a) Task 1 (b) Task 2 (c) Task 3 (d) Task 4

Fig. 10. The Comparison of Topology-enhanced Method and Topology-blind Method with Different Setting of Initial Content



(a) Task 1 (b) Task 2 (c) Task 3 (d) Task 4

Fig. 11. The Comparison of Topology-enhanced Method and Topology-blind Method with Different Number of Participated Users

Users with similar preferences form coordination groups in order to achieve coordination. We have to decide which user will participate in which group. We use a cluster-based bargain mechanism [6], in which the corresponding cooperation topology is a neg-star topology the members of which is clique structures.

Task 2 Ticket Allocation
Different coordination groups may target on the same flight. We use a cluster-based resource allocation mechanism [15], in which the corresponding cooperation topology is a clique topology.

Task 3 Flight Selection (simple situation)
In simple flight selection, users declare their choices on different flights, and the coordinated flight should be decided based on the users choices. We use an auction-based selection mechanism [13], in which the corresponding cooperation topology is a combination of a pos-star topology and a neg-star topology.

Task 4 Flight Selection (complicated situation)
In complicated flight selection, users declare detailed preference on different flights, and the coordinated flight should be decided based on all of the user's preferences. We use an auction-based conflict reconciling mechanism [2], in which the corresponding cooperation topology is a combination of a pos-star topology and a neg-star topology.

B. Experimental Setup

We implement our content-based network in JAVA and run all experiments on a Cure2 computer with 2GB of main memory. We simulate a connected network consisting of 100 nodes. Users are assigned to network nodes randomly. The user-declared content is randomly generated according to the simulated scenario.

Each of the listed coordination tasks is hard-coded in our prototype as pre-defined communication workloads. The workload consists of several rounds of message exchange, in which the messages are pre-defined. We implement the forwarding mechanism of a conversional content-based network [4] as *topology-blind* method. We refer to our method as *topology-enhanced* method. In the evaluation, messages processed by topology-blind method declare content without using cooperation topology, while messages processed by topology-enhanced method declare content using cooperation topology.

Since a network always undertakes couples of communication tasks simultaneously, task-independent initial content is generated on each network node. We inject 10,000 contents to each node as the initial content. All of these contents are conjunctions of randomly generated predicates.

The evaluation is carried out at both node level and network level. At node level, we evaluate the efficiency of the topology-enhanced forwarding mechanism. We use *average forwarding time per message* [4] as our metric. At network level, we measure the overhead brought by the topology-enhancement in accomplishing different coordination tasks. The simulation for each coordination task runs ten times and uses the average value as the result.

C. Result and Analysis

1) Effectiveness of Topology-Enhanced Method: The major concerns of our evaluation are to find out whether our topology-enhanced method overwhelms conversional topology-blind method in efficiency, and whether our method brings affordable overhead. Figure 6 shows the improvement of message forwarding efficiency at node level. Apparently, our topology-enhanced method dramatically decreases the average forwarding time per message comparing with topology-blind method. Figure 7 shows a decreasing of the finish time of different coordination tasks. We notice that the node level improvement is greater than the network level improvement. This is probably because the topology-enhanced method is less effective for some bottleneck nodes. These nodes affect the network-level improvement. Another observation is that topology-enhanced method performs stably in different coordination tasks. The result shows that for topology-blind

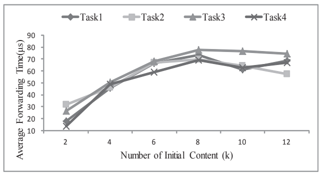


Fig. 12. The Average Forwarding Time per Message(μs) with Different Settings of Initial Content

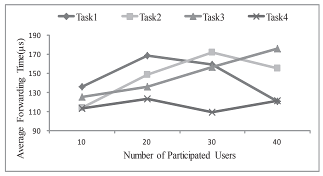


Fig. 13. The Average Forwarding Time per Message(μs) with Different Numbers of Participated Users

method, the average forwarding time varies a lot in different coordination tasks; However, the time remains in a limited range in the situation of topology-enhanced method.

Another concern of evaluation is whether the overhead is affordable in achieving the improvement. We use network initial time and index size to measure the overhead brought by topology-enhanced method. Network initial time indicates the time all nodes cost for building topology match index and predicate match index. The index size indicates the memory cost of the corresponding index. Figure 8 gives a comparison of the network initial time between topology-enhanced method and topology-blind method. Figure 9 gives the comparison of index size. Both Figures show that our method brings little overhead which takes up approximately 2% of the overall overhead brought by content-based communication.

2) Sensitivity to the Number of Initial Contents: To evaluate the stability of our method, we run the coordination tasks under different settings of node initial content, from 2,000 contents per node to 12,000 contents per node. Figure 12 shows the average forwarding time in the coordination tasks with different settings of node initial content. Figure 10 illustrates a comparison between topology-enhanced method and topology-blind method of the four coordination tasks respectively.

Generally, topology-enhanced method is more suitable for different amounts of initial content. The average forwarding time finally reaches a relatively stable level while the number of the initial content increases. The results from different coordination tasks indicate the same trend, in which the average forwarding time increases quickly from 2,000 initial contents to 6,000 initial contents and stays steadily from 8,000 contents to 12,000 contents. When the contents of a forwarding table are limited, the index items are also limited. This situation results in that the encountered topology-enhanced content cannot match with predicates in forwarding table. With the growing of the initial content, which will reflect on the size of forwarding table on nodes, more index items are established and the average forwarding time finally comes to a stable value.

3) Sensitivity to the Number of Users: Another factor related to network communication workload is the number of users within the network, since user is the only source of content-declared messages in our network setting. We perform the coordination tasks with different numbers of users to test whether our method is suitable for different communication workloads. Figure 13 shows the average forwarding time of the network nodes in four coordination tasks with different numbers of users. Figure 11 shows a comparison between topology-enhanced method and topology-blind method of the four coordination tasks respectively.

The results show that our method performs quite stably when the number of users increases in the network. The average forwarding time with different number of users concentrates in a limited range (0.1ms). There is no obvious relationship between the forwarding time and the number of users. Contrast to the result in last section, we can hardly conduct a trend between the forwarding time and the number of users. This is because the number of users is closely related to internal states of applied coordination mechanism, which finally affects the message propagation in the corresponding coordination task.

VI. Conclusions

This paper presents a network that combines content-based communication and the topology between groupware users. The proposed network aims to support content-based communication in groupware. We give a predicate-based method to define cooperation topology which can effectively describe the topology between groupware users. We also propose a multi-level index structure to support efficient matching of required cooperation topology in the forwarding mechanism of the proposed network. Evaluation result shows that the proposed network improves the message forwarding efficiency of 1 to 2 magnitude order

VII. Acknowledgments

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