An Agent-based Integrated Self-evolving Service Composition Approach in Networked Environments

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Abstract—Service composition is an important research problem in service computing systems, which combines simple and individual services into composite services to fulfill users’ complex requirements. Service composition usually consists of four stages, i.e., service discovery, candidate selection, service negotiation and task execution. In self-organising systems, there is the fifth stage of service composition: self-evolution. Most of existing works study only some of the five stages. However, these five stages should be systematically studied so as to develop an integrated and efficient service composition approach. Against this background, this paper proposes an agent-based integrated self-evolving service composition approach. This approach systematically takes the five stages of service composition into consideration. It is also decentralised and self-evolvable. Experimental results demonstrate that the proposed approach can achieve almost the same success rates while uses much less communication overhead and time consumption in comparison with three existing representative approaches.

Keywords - Service Composition, Self-organisation, Multi-agent Systems

I. INTRODUCTION

With the development of computing, service-oriented computing becomes a new paradigm for engineering modern complex systems which are composed of various services for users’ consumption [1]. Due to the increase of the complexity of users’ requirements, individual services sometimes cannot fulfill users’ requirements. Service composition becomes a necessary and effective technique to satisfy users’ complex requirements. Service composition enables simple and individual services to be dynamically combined into composite services by coordinating service providers and configuring existing services so as to meet users’ complex requirements [2]. Currently, service composition has been widely studied in many systems, e.g., cloud systems [3], multi-agent systems [4], mobile ad hoc networks [5] and sensor networks [6]. Specifically, service composition is an aggregation of atomic or composite services which collaborate to implement a set of operations in order to carry out a complex task or a business process [7].

In the last decade, a number of service composition approaches have been proposed. Most of these approaches are centralised [8], [9], while only a few of them are decentralised [10], [11]. In these centralised approaches, there is a central manager or controller who has the full knowledge of the environments and is responsible to organise service composition for consumers in the environments. The centralised approaches are very efficient in small scale environments. However, they incur computation bottleneck and suffer the single point of failure. They are also inapplicable in some environments where there is not a central manager, e.g., sensor networks [6]. The decentralised approaches overcome the computation bottleneck and the single point of failure drawback of the centralised approaches by enabling a service consumer to autonomously organise service composition. However, some decentralised approaches [12], [13] assume that each service consumer has the full knowledge of the environment. This assumption is infeasible in some large-scale environments, e.g., multi-cloud environments [14]. Other decentralised approaches [10] waive this assumption by modeling a networked environment, where each participant has a set of neighbours or acquaintances and each participant has knowledge only about its neighbours or acquaintances. These decentralised approaches, however, overlook the evolution of the operating environments, where participants may change the acquaintance relationship between each other over time and service providers may buy extra services from other participants or sell infrequently used services to other participants. Such evolution exists in a number of real world systems, e.g., multi-agent systems [15], [16], social networks [17] and peer-to-peer systems [18]. Therefore, to adapt to such evolving environments rapidly, it is important to develop a service composition approach which can self-evolve over time. Moreover, service composition consists of five stages: service discovery, candidate selection, service negotiation, task execution and self-evolution, whereas most of the existing approaches study only some of the five stages [19], [5], [20], [21]. To develop an integrated and efficient service composition approach, all the five stages should be systematically studied.

Based on this background, in this paper, an agent-based integrated self-evolving service composition approach is proposed. The proposed approach tackles two research challenges of service composition. First, self-evolution is an important property of self-organising systems [22], [16]. However, self-evolution in service composition has not been addressed properly in existing approaches [19]. Second, as described above, service composition consists of five stages which should be systematically considered to achieve an integrated service composition approach. Existing approaches, however, consider only some of the five stages [5].

In summary, the advantages of the proposed approach are as follows.

1) The proposed approach is decentralised which can avoid the computation bottleneck and the single point of failure and does not need global information.

2) The existing approaches, which consider self-evolution, study service migration only [19], whereas the proposed approach studies both service migration and relation modification. Service migration is for service exchange among participants in order to increase utilisation of services. Relation modification enables participants to remove existing and/or add new acquaintances so as to build neighbourhood with other
useful participants. Both of service migration and relation modification are important features of self-organising systems [22], [16].

3) Unlike the existing approaches which consider only some of the five stages of service composition [5], the proposed approach is the first integrated one which combines all the five stages.

4) The proposed approach is developed in a general environment instead of specific systems, e.g., mobile ad hoc networks [20]. This means that the proposed approach could be applied in various systems.

The rest of the paper is organised as follows. Section II presents related studies about service composition. Section III provides a motivating example of our research. Section IV describes the detail of our integrated self-evolving service composition approach. Experiments and the corresponding analysis are given in Section V. Section VI concludes the paper and points out the future research directions.

II. RELATED WORK

Various approaches have been proposed to handle the service composition problem [8], [9]. Most of these approaches are centralised [23], [1], [24], [25], [14].

Ardagna and Pernici [1] formalised the service composition problem as a mixed integer linear programming problem. They used loops peeling in the optimisation and took constraints posed by stateful services into consideration. In their approach, there is a centralised Concretisator module which selects the best concrete services to be invoked from a service registry for each task of the composed service according to user’s requirements and the optimisation criteria.

Kurdi et al. [14] developed a centralised combinatorial optimisation algorithm for service composition in multi-cloud environments. Their algorithm includes a cloud combiner and a service composer. The cloud combiner is used to select the appropriate cloud combination from the multi-cloud environment. The service composer takes the cloud combination as input and generates a final service composition sequence which meets user’s request.

The centralised approaches are very efficient in small scale environments. However, as all the computation and communication are handled by a central manager, the centralised approaches may incur computation and communication bottlenecks and suffer the single point of failure. In order to overcome the drawbacks of centralised approaches, decentralised approaches have also been proposed.

Moustafa and Zhang [12] proposed a reinforcement learning approach for multi-objective service composition and adaptation in dynamic uncertain environments. They used multi-objective Markov decision process to model the service composition problem. Then, two algorithms were devised to handle single policy and multiple policy multi-objective service composition based on user preferences. The solution of each of the two algorithms is a procedure that indicates how an agent selects a service in each state. Unlike Moustafa and Zhang’s single agent learning algorithm, Wang et al.’s algorithm is a multi-agent one which can perform better than a single agent learning algorithm.

Moustafa et al. [11] proposed a stigmergy-based approach to model service interactions and handle service composition. In their approach, interactions among service agents are indirect by leaving and sensing artificial pheromone. Such pheromone encodes specific information which is used to achieve service composition. Also, they developed a trust model for service selection based on the balance between the trust ranks of the concrete services and the trust ranks of the whole workflow.

These decentralised approaches distribute the decision process about service composition to each service consumer. Thus, the computation bottleneck and the single point of failure can be avoided. These decentralised approaches, however, have to use global information for service composition. For example, a service consumer is allowed to select services in the whole environment, which implies that a service consumer knows all the service providers in the environment. The use of global information is infeasible in large environments. In order to avoid using global information, some decentralised approaches were developed in networked environments, where each participant has a set of acquaintances and each participant has knowledge only about these acquaintances.

Sim [3] proposed an agent-based paradigm for cloud resource management which includes cloud search, cloud commerce and cloud service composition. In his approach, each participant has a service capability table which records a list of neighbouring participants and their services. Then, a consumer selects services for composition by consulting its service capability table to determine to which participants it should send its request message. Through this way, the number of messages exchanged among participants in the system can be significantly reduced compared to those approaches which broadcast messages to all the participants in the system.

Gutierrez-Garcia and Sim [10] devised a semi-recursive contract net protocol enhanced with service capability tables. The protocol is based on recursive calls of the contract net protocol [27] which is a distributed problem solving technique used for achieving service agreements among service consumers and service providers. By using the protocol, a service consumer can efficiently find feasible service providers which are capable of carrying out a given task.

These decentralised approaches were designed based only on local information, so they can be used in large scale environments. However, these approaches do not consider the multiple stages of service composition, including the evolution of environments, where participants may change the acquaintance relationship between each other over time and participants may buy extra services from others or sell infrequently used services to others. Some other decentralised approaches take multiple stages of service composition into consideration but they still have some limitations or differences compared to our approach.

Prinz et al. [19] studied dynamic service composition in P2P systems by introducing logical peer groups. They then proposed an approach which enables runtime composite service reconfiguration including service exchange among peers. The formation of a logical service group is carried out by an initial coordinator which collects information about all
peers required sub-service. During execution, new peers may arrive and peers’ execution properties may vary. Then, sub-
services may be exchanged among peers to guarantee the
proper execution of the system. Their approach, however, is
based on global information, while our approach is based
only on local information. Moreover, self-evolution in their
approach considers service exchange only, while self-evolution
in our approach considers both service exchange and relation
modification.

Cardellini et al. [21] proposed a decentralised service
composition approach by using a gossip protocol to support
information dissemination and decision making. In their
approach, each peer has three components: network latency
estimator, workflow manager and gossip manager. Network
latency estimator estimates the network delay between pairs of
peers in order to meet QoS requirements. Workflow manager is
responsible for initiating the composition of a new workflow
or for repairing an existing workflow. Gossip manager is
responsible for decentralised information dissemination and
decision making so as to achieve dynamic service composition
and adaptation of workflows. Their approach is fully decen-
tralised which is based only on local information. However,
their study focuses on service discovery and selection while
overlooks other stages. In comparison, our approach considers
all the five stages.

Groba and Clarke [20] presented a service composition
protocol which opportunistically allocates and invokes service
providers. They modeled a service composite as a directed
acyclic graph and a service provision as a time-varying graph.
Then, service composition is to find a mapping between the
directed acyclic graph and the sequence of time-varying
graph such that the edges between two services are enabled
for the time they interact. Their protocol is independent of
network topology and can reduce failure probability. Their
study is different from ours in the following aspects. First,
their protocol is developed in dynamic ad hoc environments,
while our approach is designed in a general environment,
which means that our approach could be applied in various
environments. Second, for service composition, their protocol
mainly focuses on three stages: service discovery, service
selection and service execution (known as service allocation
and invocation in the paper)\(^1\), while our approach studies all
the five stages. Third, in their protocol, the service composition
problem is modeled as a graph mapping problem, while in our
approach, the service composition problem is modeled as a
multi-agent resource allocation problem. Since the models and
environments are different, the solutions are entirely different.

Chen and Clarke [5] proposed a decentralised service
composition model, where a system dynamically adapts its
business process by composing its fragments on-demand to
meet the constraints of service providers and consumers.
Their model matches \(L (L \leq 1)\) service queries to \(M \leq 1\) services by adapting abstract workflows and their
concrete implementation details. Their work is carried out in
ad hoc environments and focuses on two stages of service
composition: service discovery and service selection, while
our work is conducted in general environments and focuses
on all the five stages of service composition.

Compared with existing approaches, our approach is decen-
tralised, uses only local information and takes multiple
stages, including self-evolution, of service composition into
consideration.

### III. A Motivating Example

![Fig. 1. A motivating example](image_url)

This section provides an application example from target
tracking in wireless sensor networks (WSNs). It should be
noted that the target tracking in WSNs is an application
example only. The proposed service composition approach will
be developed in a general environment rather than any specific
networks or systems.

In Fig. 1, each circle represents a sensor node. Suppose
that sensor 1 has detected a target and needs to identify
and track the target. To identify and track a target, sensor 1
needs two services: identification service and tracking service.
Sensor 1, however, does not have such two services and
needs to ask other sensors in the network for help. This is
a wireless sensor network, so sensor 1 has knowledge only
about its neighbouring sensors, i.e., sensor 2 and sensor 3.
Sensor 1 will inquire sensor 2 and sensor 3 that if they
can provide any of the services. In the case that sensor 2
and sensor 3 cannot provide the required services, they will
inquire their neighbours. This process will continue until the
pre-set TTL (Time To Live) value for the discovery of each
service is reached (stage 1). After the search process, several
service providers may be found for each service request. Then,
sensor 1 will select providers for the service requests based
on some criteria (stages 2 and 3). After execution of these
services (stage 4), sensor 1 will evolve (stage 5). Sensor 1
may remove less efficient neighbours or may add efficient
sensors as new neighbours. In this example, the removed or
added neighbours are logic neighbours rather than physical
neighbours, because physical neighbours are formed based on
sensors sensing ranges and thus cannot be changed arbitrarily.
In WSNs, sensors can change physical neighbours by adjusting
their sensing ranges. The detailed discussion of discovery and
change of physical neighbours in WSNs is out of the scope
of this paper. Interested readers can refer to [28].

Specifically, the service workflow of the example tracking
network is given in Fig. 2. As stated in [29], [30], there are
roughly seven types of services used in a tracking network.
\(S_1\) is the target discovery service which is used for discovering
that a target appears in the network. \(S_2\) is the target detection
service which is used to locate the position of the target. \(S_3, S_4\)
and \(S_5\) constitute the target identification service, where \(S_3\)
is the target feature extraction service, \(S_4\) is the target feature
classification service, and \(S_5\) is the target feature recognition

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\(^1\)Groba and Clarke [20]’s protocol also considers other two stages: synchro-
nisation and communication. The two stages have to be considered in ad hoc
environments but are not necessary in general environments. If our approach
is applied to ad hoc or other communication environments, these two stages
will be taken into account.
service. \( S_6 \) is the target tracking service which is used to chase the target. \( S_6 \) may be provided by multiple service providers, i.e., sensors, as the target may travel in the network and a sensor is not powerful enough to cover the area that the target travels through. \( S_7 \) is the processing and reporting service which is used to process the collected information and report the outcome to the user.

![Fig. 2. The service workflow](image)

In this application example, the WSN is a decentralised network. Thus, those centralised service composition approaches are most likely inadequate here. Also, in WSNs, the communication capability of sensors is very limited [31], [32]. Thus, those decentralised service composition approaches, which have to use global information, are also most likely inadequate, as the acquisition of global information involves large overhead of communication. Finally, as WSNs are self-organising systems [33], those decentralised service composition approaches, which do not consider the evolution of environments, are again most likely inadequate here either. Therefore, a decentralised service composition approach, which considers multiple stages of service composition and uses little communication overhead, is necessary and the aim of this paper is to develop such an approach.

### IV. THE INTEGRATED SELF-EVOLVING APPROACH DESIGN

In this section, we first formulate the problem. Then, an overview of the proposed approach is given. Finally, the details of the proposed approach are presented.

#### A. Problem Formulation

The proposed approach is developed in a distributed networked environment which is defined as an acquaintance network\(^2\) in Definition 1.

**Definition 1: (Acquaintance Network).** The acquaintance network is defined as an undirected graph \( G = (V, E) \). \( V \subseteq V \times V \) is the set of edges which link participants. Two participants, \( v_i \) and \( v_j \), are acquaintances of each other if \( (v_i, v_j) \in E \). Each participant, \( v_i \), has an acquaintance set \( N_i = \{ v_j \mid (v_i, v_j) \in E \} \). In addition, \( N_i^* = N_i \cup \{ v_i \} \) is the acquaintance set which includes \( v_i \) itself. Each participant can directly interact only with those participants in its acquaintance set.

Each participant, \( v_i \), in the acquaintance network has a set of services recorded as \( S_i \). Each participant has three possible roles: consumer, broker and provider which are defined in Definition 2.

**Definition 2: (Consumer, Broker and Provider).** When a participant initialises a service request, this participant is called a service consumer. When a participant provides a service to a consumer, this participant is called a service provider. When a participant receives a commitment from a consumer to find proper providers, this participant is called a broker.

According to Definition 2, the role of a participant is based on a specific service request. As each participant has a set of services, a participant can be a consumer, a broker and a provider simultaneously. For example, a participant, \( v_i \), needs a service, \( s_1 \), so for service \( s_1 \), \( v_i \) is a consumer. Meanwhile, \( v_i \) provides service \( s_2 \) to participant \( v_j \), so for service \( s_2 \), \( v_i \) is a provider. Also, \( v_i \) has a commitment from participant \( v_k \) for service \( s_3 \) to find a proper provider, so for service \( s_3 \), \( v_i \) is a broker. As these processes can happen concurrently, \( v_i \) can be a consumer, a broker and a provider simultaneously.

The service composition problem in this paper is described in Definition 3.

**Definition 3: (Service Composition).** In an acquaintance network, when a consumer has a complex task, \( T \), which needs a set of services to fulfill, \( T \leftarrow \{ s_1, ..., s_m \} \), how to find and select proper providers for these services is called service composition in this paper\(^3\).

In Definition 3, the number of required services of a complex task depends on the type of the task. For example, in Section III, the target chasing task needs five services: the target discovery service, the target detection service, the target identification service, the target tracking service, and the processing and reporting service. Furthermore, the target identification service can be considered as a sub-task which needs three services: the target feature extraction service, the target feature classification service and the target feature recognition service. As our approach is developed in a general environment, we do not set a specific number of services for a complex task. Instead, we use a variable, \( m \), to represent the number of required services.

#### B. Overview

To make participants autonomous, each participant is equipped with an intelligent agent which behaves on behalf of the participant. Then, various intelligent agent technologies, e.g., multi-agent learning, multi-agent trust management and multi-agent negotiation, can be used. The use of agent technologies in service composition can overcome the limitations in traditional service composition approaches [11]. Here, an intelligent agent is an entity which can make rational decisions autonomously in a dynamic environment. An intelligent agent blends pro-activeness and re-activeness, shows rational commitments to decision making and exhibits flexibility when facing an uncertain and changing environment [37].

\(^2\)As this paper aims at developing a service composition approach, the detailed discussion of establishment and maintenance of networks is out of the scope of this paper. Interested readers can refer [34], [35], [36] for the establishment and maintenance of networks.

\(^3\)Accurately, service composition should include the building up process of a composite service. The building up process of a composite service, however, depends on specific applications. As the proposed service composition approach is developed in a general environment, we do not consider the building up process of a composite service in this paper.
When a consumer has a complex task to fulfill, the consumer agent starts the service composition using the proposed approach. The service composition approach consists of the following five stages.

1) Service discovery: For each of the required service, the consumer agent searches the acquaintance network directly or via its acquaintances.

2) Candidate selection: After search, the consumer agent uses a trust model to select the candidate service providers.

3) Service negotiation: After selection, the consumer agent negotiates with these candidate provider agents in order to achieve service agreements, one service is used to carry out the task.

4) Task execution: Then, the consumer agent chooses a set of service agreements for the required service. In the set of service agreements, one service is used to carry out the task and other services are used as backup in case that the service in use unexpectedly fails.

5) Network evolution: Finally, the consumer agent evaluates its current status, based on historical data, to make decisions whether it needs to modify relationships with its acquaintances and whether it needs to buy or sell some services.

The mechanism or algorithm for each stage will be described in detail in the following sub-sections.

C. Stage 1: service discovery

The service discovery process is based on local information, which is described in Algorithm 1 as follows.

**Algorithm 1:** Service discovery process

```plaintext
for each participant \( v_i \in V \) do
  for each service request, \( s_k \), in task \( T \) of \( v_i \) do
    \( CandList_{(s_k)} \leftarrow \emptyset; \)
    if any acquaintance \( v_j \), where \( v_j \in N^i \), can provide service \( s_k \) then
      \( CandList_{(s_k)} \leftarrow CandList_{(s_k)} \cup \{v_j\}; \)
    while \( TTL(s_k) > 0 \) do
      m selects acquaintances as brokers;
      if any acquaintance \( v_j \) of these brokers can provide service \( s_k \) then
        \( CandList_{(s_k)} \leftarrow CandList_{(s_k)} \cup \{v_j\}; \)
      \( TTL(s_k) \leftarrow TTL(s_k) - 1; \)
```

For each service request \( s_k \) of a participant \( v_i \), \( v_i \) creates a candidate list \( CandList_{(s_k)} \) and initialises the list as an empty set (Lines 2 and 3). First, \( v_i \) inquires its acquaintances whether they have the service \( s_k \) (Line 4). Those participants which have the service \( s_k \) will be added into the candidate list \( CandList_{(s_k)} \) (Line 5). Then, \( v_i \) selects \( m \) acquaintances from \( N_i \) as brokers and commits the selected acquaintances to find candidates for service \( s_k \) (Line 7). This selection is based on the performance of \( v_i \)’s acquaintances, which is described in Algorithm 2. Each broker inquires its acquaintances about service \( s_k \) and replies \( v_i \) which acquaintances have service \( s_k \) (Line 8). These acquaintances, which have service \( s_k \), will be added in the candidate list \( CandList_{(s_k)} \) (Line 9). Afterwards, each broker continues the search process by selecting \( m \) acquaintances as new brokers until \( TTL(s_k) \) reaches 0. Here, local information means that each participant knows only its neighbours, i.e., acquaintances. If a participant wants to have more information, it has to inquire its neighbours.

In Algorithm 1, the loop is used by participants to obtain more information. The loop is controlled by a parameter \( TTL \), which is set by users, to avoid infinite search in the network. Therefore, many participants can be searched in a loop entirely depends on the value of \( TTL \). Different services may have different values of \( TTL \). For example, important services can be set a relatively larger \( TTL \), compared to less important services so as to have more providers found.

**Algorithm 2:** Broker selection

```plaintext
\* Initialisation *
for each acquaintance \( v_j \in N_i \) do
  \( \text{Let the performance of } v_j \text{ be } Q(v_j); \)
  \( \text{Let the probability of selecting } v_j \text{ as a broker be } p(v_j); \)
  \( \text{The probability distribution over acquaintances is recorded as } P = (p(v_1), ..., p(v_{|N|})), \text{ where } |N| \text{ means the number of } v_j \text{ and } \sum_{j \leq |N|} p(v_j) = 1 \text{ and } 0 < p(v_j) < 1; \)
\text{initialises each } Q(v_j) = 0 \text{ and } p(v_j) = \frac{1}{|N|};

\* Selection and adjustment *
for each acquaintance \( v_j \in N_i \) do
  \( Q(v_j) \leftarrow (1 - \alpha)Q(v_j) + \alpha \cdot r_j; \)
  \( p(v_j) \leftarrow p(v_j) + \zeta(Q(v_j) - r_j); \)
\( P \leftarrow \text{Normalise}(P); \)
```

In Algorithm 2, \( v_i \) first initialises the performance of each acquaintance and the probability of selecting each acquaintance (Lines 2-6). Because initially, \( v_i \) is not aware of its acquaintances’ performance, it simply sets the performance of each acquaintance to \( Q(v_j) = 0 \) and sets the probability of selecting each acquaintance equally to \( p(v_j) = \frac{1}{|N|} \). Then, \( v_i \) selects \( m \) acquaintances as brokers based on probability distribution \( P \) (Line 8). For example, \( v_i \) has three acquaintances and the probability distribution over the three acquaintances is \( P = (0.2, 0.3, 0.5) \). Then, \( v_i \) has the probability 0.2 to select the first acquaintance, the probability 0.3 to select the second acquaintance and the probability 0.5 to select the third acquaintance, as a broker.

When these brokers finish their job, \( v_i \) evaluates the performance of each acquaintance and assigns a reward \( r_j \) (Line 9). For those acquaintances which are not selected as brokers, they are assigned a reward 0. For the brokers, the reward of a broker is based on how many candidates it has found for \( v_i \)’s task \( T \). The more candidates a broker has found, the more reward the broker is assigned. For example, suppose a threshold is set as 3. Then, if a broker has found 5 candidates, this broker is assigned a reward 2, where \( 2 = 5 - 3 \); whereas if another broker has found only 2 candidates, this broker is assigned a reward \(-1 \), where \(-1 = 2 - 3 \).

After the assignment of reward to each acquaintance, \( v_i \) adjusts the performance of each acquaintance and the probability of selecting each acquaintance (Lines 10-13). In Line 12, \( v_i \) adjusts the performance of each acquaintance, \( Q(v_j) \), based on the acquaintance’s current performance and the reward, \( r_j \), assigned during the service discovery for task \( T \), where \( 0 < \alpha < 1 \) is the learning rate which is a constant coefficient. Then, in Line 13, the probability of selecting each acquaintance is updated after the selected acquaintances finish
their jobs. Such update is based on how the acquaintances work and the former value of the probability. Specifically, in this algorithm, the update is based on the current probability, \( p(v_j) \), the new performance value, \( Q(v_j) \), and the average reward of all the acquaintances, \( \bar{r} \), where \( 0 < \zeta < 1 \) is the learning adaptation rate which is a constant coefficient. Finally, in Line 14, the function \( \text{Normalise()} \) is used to constrain \( P \) to a valid probability distribution, i.e., \( \sum_{1 \leq j \leq |N|} p(v_j) = 1 \) and \( 0 < p(v_j) < 1 \), and \( \text{Normalise}(P) \) has the minimum Euclidean distance to \( P \).

D. Stage 2: candidate selection

After Stage 1, consumer \( v_i \) has obtained a candidate list which stores providers that can provide \( v_i \)'s requested service. Before \( v_i \) negotiates with these providers to achieve service agreements, \( v_i \) uses a trust model to select only the trustworthy candidates. To assist each participant to select the trustworthy candidates for service negotiation, a trust model is developed which is based on Dezert-Smarandache theory (DSmT) [38]. Dezert-Smarandache theory has good expressiveness and low computational complexity for trust representation.

Let \( T \) mean that the given consumer considers a provider to be trustworthy and \( \Theta = \{ T, \neg T \} \) be the general framework of discernment. The hyper-power set of \( \Theta \) is represented as \( H^\Theta = \{ \emptyset, \{ T \}, \{ \neg T \}, \{ T \cap \neg T \}, \Theta \} \). Function \( m : H^\Theta \rightarrow [0, 1] \) is a general basic belief assignment where

\[
\begin{align*}
m(\emptyset) &= 0, \\
\sum_{B \subseteq H^\Theta} m(B) &= 1. 
\end{align*}
\]

Thus, \( m(\{ T \}) + m(\{ \neg T \}) + m(\{ \Theta \}) + m(\{ T \cap \neg T \}) = 1 \), as \( m(\emptyset) = 0 \). In Equation 1, \( B \) represents an element in set \( H^\Theta \).

The trust model is defined as a tuple, \( T_j^i = \{ m_j^i(\{ T \}), m_j^i(\{ \neg T \}), m_j^i(\{ \Theta \}), m_j^i(\{ T \cap \neg T \}) \} \), where \( i \) and \( j \) represent a consumer \( v_i \) and a provider \( v_j \), respectively. Each element in \( T_j^i \) is described as follows: 1) \( m_j^i(\{ T \}) \) is the degree of \( v_i \) trusting \( v_j \); 2) \( m_j^i(\{ \neg T \}) \) is the degree of \( v_i \) distrust \( v_j \); 3) \( m_j^i(\{ \Theta \}) \) is the degree of uncertainty about the trustworthiness of \( v_j \) to \( v_i \). This case happens when \( v_i \) lacks evidence about \( v_j \). If \( v_i \) has no evidence at all, \( m_j^i(\{ \Theta \}) = 1 \); otherwise, \( m_j^i(\{ \Theta \}) < 1 \); 4) \( m_j^i(\{ T \cap \neg T \}) \) is the degree of contradiction about the trustworthiness \( v_j \) to \( v_i \). This case is caused by the situation, for example, that \( v_i \) trusts \( v_j \) but other participants, which provide \( v_i \)'s opinions, distrust \( v_j \). Therefore, \( v_i \) gets into contradiction.

Initially, trust between any two participants is \( T_j^i = \{ m_j^i(\{ T \}) = 0, m_j^i(\{ \neg T \}) = 0, m_j^i(\{ \Theta \}) = 1, m_j^i(\{ T \cap \neg T \}) = 0 \} \). Trust is, then, acquired through service usage between participants. Suppose that \( v_i \) is evaluating the trust of \( v_j \) which has provided \( x \) services to \( v_i \). \( v_i \) uses the notion, \( SL \) (satisfaction Level), to express how it is satisfied with each of \( v_j \)'s services. Therefore, for \( x \) services, there are \( x \) \( SL \) values. \( SL \) is in the range of \( [0, 1] \) and its calculation depends on how well the service agreement is completed. If \( v_j \) can provide \( v_i \) a service which matches the service agreement, \( v_i \)'s estimation on this service is \( SL = 1 \); otherwise, the value of \( SL \) is less than \( 1 \). For example, \( v_j \) is an Internet service provider and \( v_i \) is a user. In the service agreement, \( v_j \) guarantees that the bandwidth is no less than \( 4 \)Mbps. Thus, if the bandwidth can reach \( 4 \)Mbps or above, \( v_i \)'s satisfaction level \( SL \) is \( 1 \). However, if, due to some reason, the bandwidth does not reach \( 4 \)Mbps, then \( v_j \)'s satisfaction level \( SL \) will be less than \( 1 \). The lower the bandwidth value is, the lower \( v_i \)'s satisfaction level is. Based on satisfaction level, \( v_i \)'s trust evaluation on \( v_j \) can be calculated as follows. The value of \( m_j^i(\{ T \}) \) is set to the number of services, where \( v_j \)'s satisfaction level on these services is larger than or equal to \( \Omega \). The value of \( m_j^i(\{ \neg T \}) \) is set to the number of services, where \( v_j \)'s satisfaction level of these services is less than or equal to \( \omega \). The value of \( m_j^i(\{ \Theta \}) \) is set to the number of services, where \( v_j \)'s satisfaction level on these services is between \( \omega \) and \( \Omega \). Here, \( \omega \) and \( \Omega \) are lower and upper thresholds, respectively. After calculation, the elements in \( T_j^i \) are then normalised to satisfy \( \sum_{B \subseteq H^\Theta} m_j^i(B) = 1 \). Such trust evaluation is carried out after a predefined number of task executions.

In addition, \( v_i \) may ask one of its acquaintances, say \( v_k \), for trust evaluation to \( v_j \). Then, \( v_i \) combines \( v_k \)'s opinion with \( v_i \)'s own view to \( v_j \). This is trust combination. Moreover, there might be another case. \( v_i \) asks \( v_k \)'s opinion of \( v_j \) but \( v_k \) may have no idea about \( v_j \). \( v_k \) then inquires one of its acquaintances, \( v_l \)'s opinion to \( v_j \). This is trust transitivity. The details of trust and trust transitivity can be found in [15].

Based on the trust model, the candidate selection is described in Algorithm 3.

**Algorithm 3: Candidate selection**

```
for each candidate service provider, \( v_j \), in CandList(k) do
  if \( m_j^i(\{ T \}) \geq \rho \) then
    \( v_i \) enquires its acquaintances' opinions about \( v_j \);
  \( v_i \) syncretises its acquaintances' opinions via trust combination and trust transitivity;
  if \( m_j^i(\{ T \}) < \rho \) then
    \( \text{CandList}(k) \leftarrow \text{CandList}(k) - \{ v_j \} \);
```

In Algorithm 3, for each candidate, \( v_j \), in \( \text{CandList}(k) \), if the degree of \( v_i \) trusting \( v_j \) is larger than or equal to a pre-defined threshold, \( \rho \), where \( 0 < \rho < 1 \), then \( v_i \) asks its acquaintances' opinions about \( v_j \) (Line 1-3). Afterwards, \( v_i \) combines its acquaintances' opinions via trust combination and trust transitivity (Line 4). If, after the opinion combination, the degree of \( v_i \) trusting \( v_j \) becomes less than the threshold, \( \rho \), then \( v_i \) is removed from the candidate list (Lines 5 and 6).

E. Stage 3: service negotiation

After Stage 2, the candidate list has been pruned. \( v_i \) then starts the service negotiation for its service request \( s_k \) with the service providers which remain in the candidate list. The negotiation protocol developed in this paper extends the alternating offers protocol [39] by allowing an agent to make multiple service agreements with other agents and to cancel temporary agreements without paying penalty. The alternating offers protocol [39] is powerful and easy to implement, and it has been widely used for bilateral bargaining [40].

There are four possible actions that a service consumer and a service provider can take.

- **quote** \( q \), where \( q \) is a consumer's quote to a provider. A quote is determined by four factors which are the pressure of deadline, the consumer’s reserved price for the service, the
probability of reaching an agreement and the competition of the required resource.

- **accept**. When a provider receives a quote, it can accept the quote, which results in a temporary agreement made with the consumer.

- **counter_quote**. If a provider is not happy with a quote, it can send back a counter-quote for its service. A counter-quote is determined by three aspects which include the provider’s reserved price for the service, the probability of reaching an agreement for the service and the competition of the service.

- **cancel**. After a temporary agreement is achieved by a consumer and a provider, any one of them can cancel the temporary agreement without paying penalty. However, cancellation penalty applies on a backup agreement and a final agreement.

The negotiation protocol is described in Algorithm 4.

Algorithm 4: Service negotiation

\[
\begin{align*}
&\text{\# Suppose } v_i \text{ is a consumer and } v_j \text{ is a provider} \star \text{ \#} \\
&\text{while } t < \text{the deadline of the task do} \\
&\quad v_i \text{ generates a quote } o \text{ to } v_j; \\
&\quad \text{if } v_j \text{ accepts } o \text{ then} \\
&\quad\quad A^T(v_i) \leftarrow A^T(v_i) \cup \{o\}; \\
&\quad\quad A^T(v_j) \leftarrow A^T(v_j) \cup \{o\}; \\
&\quad\quad \text{return}; \\
&\quad \text{else} \\
&\quad\quad v_j \text{ generates a counter-quote } o' \text{ to } v_i; \\
&\quad\quad \text{if } v_i \text{ accepts } o' \text{ then} \\
&\quad\quad\quad A^T(v_i) \leftarrow A^T(v_i) \cup \{o'\}; \\
&\quad\quad\quad A^T(v_j) \leftarrow A^T(v_j) \cup \{o'\}; \\
&\quad\quad\quad \text{return}; \\
&\quad\quad \text{else} \\
&\quad\quad\quad \text{continue}; \\
\end{align*}
\]

In Algorithm 4, before the deadline of the task, a consumer and a provider can alternately propose quotes and counter-quotes until an agreement is reached. In Line 3, consumer \( v_i \) generates a quote \( o \) to provider \( v_j \), where \( o = \langle pr, pe \rangle \). Each of the elements in \( o \) can be calculated using the following equations.

\[
pr = \left\{ \begin{array}{ll}
\frac{res \cdot pr_{v_i}}{\left[ A^T(v_j) \right]} \cdot \frac{t - \text{arrive}(s_k)}{\text{start}(s_k) - \text{arrive}(s_k)} & \delta(t) \text{ if } A^T(v_i) = 0 \\
\frac{\text{start}(s_k) - \text{arrive}(s_k)}{\Delta(t)} & \text{otherwise} \\
\end{array} \right.
\]

\[
pe = \frac{pr}{\text{exe}_{v_j}}
\]

In Equation 2, \( pr \) is the price that \( v_j \) quotes to \( v_j \), \( res \cdot pr_{v_i} \) is the reserved price of \( v_i \) for the requested service. \( arrive(s_k) \) is the arrival time of service request \( s_k \), while \( start(s_k) \) is the latest start time of \( s_k \). \( t \) means current round. \( \delta(t) \) is the difference of \( v_j \)'s quoting prices between the last round, \( t - 1 \), and the current round, \( t \). \( \Delta(t) \) is the difference of \( v_j \)'s quoting prices between the initial round, 0, and the current round, \( t \). In Equation 2, it can be seen that the quoting price is determined by the \( v_i \)'s reserved price, \( res \cdot pr_{v_i} \), the left time till the deadline (i.e., the pressure of deadline), the number of temporary agreements that \( v_i \) has achieved (i.e., the probability of reaching an agreement), \( [A^T(v_i)] \), and the concession that the negotiating partner \( v_j \) has made (i.e., the competition of the required resource), \( \frac{\delta(t)}{\Delta(t)} \).

In Equation 3, \( pe \) is the basic penalty and \( \text{exe}_{v_j} \) means the total time steps, during which \( v_i \) needs to use \( v_j \)'s service to execute the task. The actual penalty that \( v_i \) has to pay \( v_j \) depends on how long \( v_i \) has used \( v_j \)'s service. For example, suppose that \( pr = 100 \) and \( \text{exe}_{v_j} = 20 \), so \( pe = \frac{100}{20} = 5 \).

Now, \( v_i \) has used \( v_j \)'s service for 12 time steps and \( v_j \) wants to cancel the agreement (i.e., stopping using \( v_j \)'s service), then \( v_i \) has to pay \( v_j \) penalty 60, where \( 60 = pe \times 12 \).

After receiving an offer \( o \) from \( v_j \), in Line 4, \( v_i \) evaluates whether the offer \( o \) is acceptable. This evaluation is based on how much revenue \( v_i \) could get (Equation 4), where \( cost \) is the cost that \( v_j \) spends to provide the requested service.

\[
rv = pr - cost
\]

If the revenue, \( rv \), is larger than a threshold, \( v_j \) accepts \( o \) and a temporary agreement is achieved (Lines 5 and 6). Otherwise, \( v_j \) generates a counter-quote \( o' = \langle pr', pe' \rangle \) (Line 9). The calculation of \( pr' \) is similar to Equation 2 except that provider \( v_j \) does not have a deadline for its service, while the calculation of \( pe' \) is the same as Equation 3. Then, Lines 10-12, if \( v_i \) accepts the counter-quote, a temporary agreement is achieved. Otherwise, the negotiation goes into the next round.

At the end of this stage, for each service request \( s_k \), consumer \( v_i \) may have achieved a set of temporary agreements, where each temporary agreement is signed with an individual provider. Consumer \( v_i \) selects a provider \( v_j \) to provide service \( s_k \) for task execution. The temporary agreement between \( v_i \) and \( v_j \) now becomes a final agreement. Consumer \( v_i \) also selects several providers for backup and the temporary agreements between \( v_i \) and these backup providers become backup agreements. To achieve a backup agreement, \( v_i \) has to pay the corresponding backup provider a non-refundable deposit. The amount of deposit can be set as equal to the basic penalty. Finally, \( v_i \) cancels the rest of temporary agreements.

F. Stage 4: task execution

As described above, after Stage 3, consumer \( v_i \) has achieved a set of temporary agreements for each service request and \( v_i \) has to select one provider from the temporary agreements for each service request. In this stage, an Integer Programming (IP) based method [41, 23] is employed by consumer \( v_i \) to select one provider for each service request for task execution. For an IP problem, there are three inputs: a set of variables, a set of constraints and an objective function. Both the objective function and the constraints must be linear. The aim of IP is to maximise or minimise the objective function by adjusting the values of the variables under the given constraints. The output of an IP problem is the maximum (or minimum) value of the objective function and the values of variables along with that maximum (or minimum) value.

The problem of selecting a provider for each service request can be modeled as an IP problem as follows. We first introduce a binary indicator, \( x_{jk} \), where \( x_{jk} = 1 \) if provider \( v_j \) is selected for service request \( s_k \) and \( x_{jk} = 0 \) otherwise. We also introduce another binary indicator, \( y_k \), where \( y_k = 1 \) if service request \( s_k \) is critical and \( y_k = 0 \) otherwise. Each service request, \( s_k \), has a start time, \( start_k \). A provider, \( v_j \), needs execution duration time, \( dur_{jk} \), to execute service request \( s_k \) with price \( pr_{jk} \) and reliability \( reli_{jk} \). The constraints are formally expressed as follows.
s must be executed after the execution of s. Thus, communication overhead can be minimised while the overall execution duration time and the total usage/service management cost so as to improve v’s overall utility.

The three problems, namely modifying relationships, buying services and selling services, can be modeled as a decision making problem, i.e., whether or not to do something based on some observation. The decision making process of v modifying relationship with v is described as follows. The decision making process of other problems is similar.

Suppose that v is one of v’s acquaintances. Every time, when v’s task execution is completed, v has two options, i.e., whether it should keep v as an acquaintance or not. Let p0 be the probability of keeping v as an acquaintance and p1 be the probability of removing v from v’s acquaintance list. Also, let Q(ob(t), 0) be the expected reward of keeping v as an acquaintance and Q(ob(t), 1) be the expected reward of removing v from v’s acquaintance list, where ob(t) is v’s observation to v till time step t. Initially, p0 = 1, p1 = 0, Q(ob(t), 0) = 0 and Q(ob(t), 1) = 0. Then, after a task execution, t + 1, Q(ob(t + 1), 0) is updated using Equation 12, where R0 is immediate reward obtained by v for keeping v as an acquaintance during this task execution, and γ, 0 < γ < 1, is a constant learning rate.

\[ Q(ob(t + 1), 0) = Q(ob(t), 0) + p_0 \cdot \gamma \cdot (R_0 - Q(ob(t), 0)) \]  

Here, immediate reward, R0, is determined based on 1) the number of services that v provides and 2) the number of proper providers that v has found for v during this task execution. Then, after the calculation of Q(ob(t + 1), 0) using Equation 12, p0 and p1 are adjusted using Equation 13, where \( \epsilon < 1 \), is a greedy coefficient.

\[ \begin{align*}
    p_0 &= p_0 + \epsilon \cdot Q(ob(t + 1), 0) \\
    p_1 &= 1 - p_0
\end{align*} \]

After the probability adjustment, function Normalise() (Algorithm 2) is again used to project p0 and p1 to a valid probability distribution: \( 0 \leq p_0, p_1 \leq 1 \) and \( p_0 + p_1 = 1 \). Finally, v selects an option based on the probability distribution, p0 and p1. If v selects 1, namely that v decides to remove v from its acquaintance list, the above process terminates.

For the two other problems, buying/selling services, the process is similar to the above process. If v decides to buy or sell a service, v can use the methods proposed in Stages 1, 2 and 3, where in Stage 1, v searches potential sellers/buyers; then in Stage 2, v uses the trust model to select trustworthy sellers/buyers; finally, in Stage 3, v negotiates with these candidates and buys/sells services from/to the candidates which can maximise v’s utility.

As our approach is developed in a general environment, the application of it in a specific environment, e.g., sensor networks, is not studied in this paper. The application of our approach in specific environments needs corresponding modification. For example, if the approach is applied in sensor networks, as a sensor network is a resource-constrained environment, buying/selling services among sensors must be realised by using energy-efficient resource sharing techniques [42].

H. Discussion

In the proposed approach, it is assumed that for each service type, there is only one candidate service. Generally, for each
service type, a provider may have different services which may have different property values, e.g., different response times and different prices. In this paper, as the approach consists of five stages, for the ease of presentation and understanding, it is assumed that for each service type, there is only one candidate service and each provider may or may not offer the candidate service. However, the prices of the candidate services provided by different providers may be different, because the prices of the candidate services are negotiable (refer to Section IV-E). Moreover, in the proposed approach, it is not assumed that the quality of the candidate services offered by different providers is identical. Thus, the negotiable prices imply that the quality of the candidate service offered by different providers may be different. Therefore, the proposed approach can accommodate multiple candidate services, although in the current version, the multiple candidate services are not taken into account. The evaluation of the proposed approach with multiple candidate services is one of our future studies.

V. EXPERIMENT AND ANALYSIS

In this section, the proposed integrated self-evolving service composition approach, named as Self-Evo, is evaluated in comparison with three other related and representative approaches which are described as follows.

1) Mixed Integer Programming (MIP) [1]: MIP is an efficient and well-known approach for service composition in a centralised manner [23], [1]. Service composition problem can be mapped to an MIP problem by setting a set of constraints, defining a set of variables and establishing an objective function. The MIP problem is then solved by a central manager. In this experiment, the central manager is a simulated entity which is not a participant of the network. The central manager can directly communicate with any participants in the network. As the simulated network is a general network, specific communication medium is not considered.

2) Multi-Agent Reinforcement Learning (MARL) [12], [26]: MARL is a subdiscipline of multi-agent techniques. In MARL, each agent learns by trial-and-error interaction with a dynamic environment. Agents can autonomously adjust their behaviour based on the feedback from the environment so as to achieve better results in the future. Thus, using MARL, systems inherently have good self-adaptability. In existing MARL based service composition approaches, users are modeled as agents and services are modeled as actions, where in different states, users take different actions and obtain different rewards. Based on the rewards, users adjust the probability distribution over their actions, i.e., services, for service selection in the future. However, although agents can make decisions individually without central control, agents still need global information.

3) Service Capability Table based approach (SCT) [10]: SCT based approach does not need central control or global information. Each agent has a service capability table which records a list of acquainted agents and their service capabilities, which implies that each agent has limited knowledge of the environment. Consumer agents request services via broker agents which have two SCTs that record information about service provider agents and other broker agents. When a broker agent receives a request to carry out a service composition, the broker agent contracts services with proper provider agents in its SCT if possible, otherwise the broker agent subcontracts to other broker agents in its SCT to fulfill the unresolved service requirements.

In this experiment, the performance of the four approaches, i.e., our Self-Evo and three above-mentioned representative approaches, is evaluated by measuring three quantitative metrics: success rate, communication overhead and time consumption.

1) Success rate is the percentage of successful service composition. As success rate is a ratio between the number of successful service composition and the total number of attempted service composition, it does not have a unit.

2) Communication overhead is the average number of messages used for a successful service composition. The size of a message is neglected, as it is the same in all the four evaluated approaches in the experiment. Thus, communication overhead does not have a unit.

3) Time consumption is the average time consumed for a successful service composition. The unit of time consumption is millisecond (ms).

A. Experimental Setup

The experiment was conducted in both static and dynamic environments. The network structure is randomly generated, where every two participants are acquaintances of each other with a specific probability. The average number of neighbours of each agent is set to 8. In the static environment, the number of participants in the environment is fixed, while in the dynamic environment, participants can join and leave the environment dynamically. In the static environment, the experiment was conducted in three scenarios. In the first scenario, it is measured that how the performance of the four approaches changes with increase of network size. In the second scenario, it is measured that how the performance of the approaches changes with the variation of task introduction probability. Task introduction probability means that at each time step, with which probability a task is introduced into the environment. In the third scenario, it is measured that how the performance of the approaches changes with the variation of service allocation probability. Service allocation probability means that with which probability a service is allocated to a participant. In the dynamic environment, in addition to the above three scenarios, there is the fourth scenario, where it is measured that how the performance of the approaches changes with the variation of the probability of participant leaving and joining. This experiment is simulated by using a general programming language, Java. Then, ‘agent’ is initially programmed as a class and then all agents are the objects of this class. Services are simply represented as integers and each agent is randomly allocated some of the services. A task is programmed as an array. Each element in the array is an integer which represents the required service. The number of services required by a task is randomly generated. Moreover, the experiment is run on an Intel i5-2450m 2.5GHz Windows

4Although target tracking in WSNs is used as an example in this paper, the proposed approach will not be evaluated in WSNs. This is because our approach is developed in a general environment and should not be limited in WSNs only. Instead, we evaluate our approach in a general environment to ensure that the experimental results are representative in most operating environments.
10 PC with 10GB RAM. The experimental results are obtained by averaging 100 runs. Here, we use Java instead of a specific agent platform to implement the experiment, because 1) this paper mainly studies service composition instead of agent technologies which are used as development methods; 2) the aim of the experiment is to evaluate the effectiveness of the proposed approach; and 3) using specific agent platforms is certainly feasible for the implementation of agents but will not affect the effectiveness of the proposed approach. Therefore, specific agent platforms are not necessary in the experiment.

The values and meanings of the parameters used in the experiment are listed in Table I. These values were chosen experimentally to provide the best results.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>α, β, γ</td>
<td>0.2, 0.3, 0.2</td>
<td>Learning rates</td>
</tr>
<tr>
<td>ρ</td>
<td>0.7</td>
<td>Threshold for candidate selection</td>
</tr>
<tr>
<td>ε</td>
<td>0.1</td>
<td>Greedy coefficient</td>
</tr>
</tbody>
</table>

B. Experimental Results: Static Environment

1) The first scenario: Fig. 3 demonstrates the performance of the four approaches in different network scales. In this scenario, the task introduction probability is fixed at 0.3 and the service allocation probability is fixed at 0.5.

In Fig. 3(a), it can be seen that with the increase of network scale, the success rates achieved by MIP and MARL decrease gradually, while the success rates achieved by SCT and our Self-Evo keep relatively steady. This is because both MIP and MARL need information of all the participants in the network and when the number of participants in the network increases, the amount of required information also rises. Thus, the computation overhead under MIP and MARL becomes huge. Due to the limitation of processing capability, some tasks cannot be processed on time, so the success rate decreases. For SCT and Self-Evo, no global information is required and each participant requests services only from its acquaintances, so the increase of network scale does not have much impact on SCT and Self-Evo. It should be noted that the success rate achieved by our Self-Evo is higher than that achieved by SCT. This is because under Self-Evo, network structures evolve over time, where each participant keeps only useful acquaintances and services after evolution. Therefore, a service composition for a task can be completed faster. In other words, more service compositions can be completed in a period by using Self-Evo than using SCT.

In Figs. 3(b) and 3(c), it can be seen that with the increase of network scale, both the communication overhead and the time consumption under the four approaches rise. For MIP and MARL, as the two approaches need global information, the central manager in MIP and the focal consumer agent in MARL has to request information from every participant in the network. Thus, as the number of participants in the network increases, both MIP and MARL need more communication and time to obtain the global information of the network. For SCT and Self-Evo, with the increase of the number of participants, the average number of acquaintances of each participant also increases, which then incurs the increase of the communication overhead and time consumption under SCT and Self-Evo. Again, as the network structure can be optimised under Self-Evo, Self-Evo uses less communication and time than SCT.

2) The second scenario: Fig. 4 displays the performance of the four approaches with different number of tasks in the network. In this scenario, the number of participants in the network is fixed at 500 and the service allocation probability is fixed at 0.5.

In Fig. 4(a), with the increase of task introduction probability, more and more tasks exist in the network. Thus, as the two approaches need global information, the central manager in MIP and the focal consumer agent in MARL has to request information from every participant in the network. Thus, as the number of participants in the network increases, both MIP and MARL need more communication and time to obtain the global information of the network. For SCT and Self-Evo, with the increase of the number of participants, the average number of acquaintances of each participant also increases, which then incurs the increase of the communication overhead and time consumption under SCT and Self-Evo. Again, as the network structure can be optimised under Self-Evo, Self-Evo uses less communication and time than SCT.

3) Here, a focal consumer agent is a consumer agent which initialises a service composition.
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decrease. It should be noted that when the task introduction probability is larger than 0.7, Self-Evo performs better than the other three approaches, while MIP performs the worst. This is because with the increase of the number of tasks, as in MIP all the processing is based on a single central manager, tasks will overwhelm the central manager given that the processing capability of the central manager is finite. In Self-Evo, as participants can adjust their behaviour with change of the environment, the pressure of a large number of tasks can be alleviated to some extent. For example, if a consumer has a number of tasks to do, it will attempt to buy proper services from other participants and it will establish acquaintance relationship with those participants who have the required services. Such adjust can relax the task pressure.

In Figs. 4(b) and 4(c), it can be seen that with the increase of the number of tasks, the communication overhead under MIP and MARL keeps relatively steady while the time consumption under MIP and MARL increases gradually. In MIP and MARL, the communication overhead to complete a service composition is fixed and independent of the number of tasks, as only successfully completed tasks are counted in. To successfully complete a service composition for a task, the communication overhead for MIP and MARL is almost fixed, i.e., the central manager or focal consumer agent broadcasts a request message in the network, receives response messages and then calculates a solution. The time consumption under MIP and MARL increases gradually, because with the increase of the number of tasks, service compositions for some tasks may not be completed at once and have to stay in the waiting list for a while. Thus, the average time used to complete a service composition rises.

For SCT and Self-Evo, the communication overhead and time consumption rise with the increase of the number of tasks in the network. In SCT and Self-Evo, communication happens between service consumers, brokers and providers. When the number of tasks increases, available services are more and more difficult to obtain, which implies that consumers have to find and negotiate with more providers to achieve a service agreement. Thus, the communication overhead and time consumption to complete a service composition rise.

3) The third scenario: Fig. 5 displays the performance of the four approaches with different service allocation probabilities. In this scenario, the number of participants in the network is fixed at 500 and the task introduction probability is fixed at 0.3.

In Figs. 5(a), 5(b) and 5(c), with the increase of service allocation probability, the success rates achieved by SCT and Self-Evo increase gradually, while the communication and time used by SCT and Self-Evo decrease gradually. With the increase of service allocation probability, each participant possesses more services. Thus, each consumer can complete a service composition more quickly and easily, as it needs less search and negotiation for a service composition. For MIP and MARL, with the increase of service allocation probability, the success rates and communication overhead keep relatively steady, while the time consumption decreases gradually. The service composition under MIP and MARL is, to some extent, independent of the number of services that each participant has, as in MIP and MARL, the central manager and the focal consumer agent can utilise any available services in the environment no matter where the services are. Thus, the success rates and communication overhead keep almost unchanged. The decrease of time consumption is explained as follows. When each participant has few services, tasks have to wait for a relatively long time to be served. Thus, the average time consumption of each service composition is relatively long. This situation, however, is alleviated when each participant has more services, so the time consumption decreases with the increase of service allocation probability.

C. Experimental Results: Dynamic Environment

The experiment was also conducted in dynamic environments, where participants may leave or join the environment dynamically. In the first, second and third scenarios, it is set that after execution of every ten time steps, 5% existing participants leave the network and 5% new agents join the network with a specific probability. Figs. 6, 7 and 8 demonstrate a similar trend on performance variation in dynamic environments compared to static environments. In general, the performance of the four approaches are less efficient in dynamic environments than the performance in static environments. This is because for example, in dynamic environments, consumers may leave the environments before their tasks are completed. These tasks may then become unsuccessful tasks. Thus, success rates will decrease. Moreover, if providers leave the environments, consumers may have to find other providers, so the communication overhead and time consumption will increase. Moreover, our Self-Evo has to face the cold-start problem due to the use of the trust model. The cold-start problem means that when new agents join the network, their neighbours do not have information about their performance. Thus, the trust against these new agents has to be built up

\footnote{When the task introduction probability is high, e.g., 0.7, the service composition under MIP and MARL is not independent of the number of services that each participant has. This is because when the number of tasks in the environment is large and each participant has only a few services, many tasks may not be completed on time due to the lack of enough services in the environment.}
such cold-start problem has a negative impact on the performance of our approach, because along with the cold-start problem, the trust model in Self-Evo cannot effectively help participants select efficient candidates.

Comparing Fig. 6(a) with Fig. 3(a), with the increase of network scale, the success rate of SCT decreases in the dynamic environment, while the success rate of SCT keeps relatively steady in the static environment. In SCT, service composition is carried out via participants’ neighbours. In the dynamic environment, a participant’s neighbours may leave the environment before a task is completed. Thus, the success rate is affected in a negative way. This situation becomes worse in a large scale network, as the more participants in the network, the more they may leave (recalling above that 5% existing participants leave the network with a specific probability). When a participant loses most of its neighbours, it is difficult for the participant to complete any complex tasks. Although new agents may join the network, they are randomly scattered in the network and do not have to be the neighbours of that participant. Similar to SCT, in our Self-Evo, service composition is also conducted through participants’ neighbours. However, in our Self-Evo, when a participant loses its neighbours, the participant can establish new neighbour-ship with other participants and also the participant can buy
required services from other participants. Thus, the negative impact of the dynamism on Self-Evo can be alleviated to some extent via self-evolution. As MIP and MARL utilise global information, the dynamism does not have much impact on them.

Comparing Fig. 7(b) with Fig. 4(b), in the dynamic environment, when the number of tasks increases, the communication overhead of MIP and MARL also increases, while in the static environment, when the number of tasks increases, the communication overhead of MIP and MARL keeps relatively steady. As described above, if providers leave the environment, consumers may have to find other providers, which incurs extra communication and time consumption. This situation will be worse when the number of tasks increases. This is because when the number of tasks increases, a provider may serve more tasks simultaneously. If this provider leaves, more tasks will be affected and thus, more communication and time are needed.

In the exclusive scenario for the dynamic environment, Fig. 9 demonstrates the performance change of the four approaches with the variation of the probability of participant leaving and joining. For the four approaches, with the increase of the probability of participant leaving and joining, the success rates decrease while the communication overhead and time consumption increase. This means that the increase of dynamism level of the environment has negative impact on the performance of the four approaches. Since the leaving of participants implies the failure of participants, consumers or the central manager have to spend extra communication and time to counter such situation, which is certainly harmful for the overall performance. The joining of new participants can also offset such situation to some extent, but the usefulness of the new participants is limited. For MIP and MARL, if providers leave the environment, the joining of new participants can increase the probability of completing the service compositions which are left by those leaving providers. However, the joining of new participants cannot avoid the communication and time used by the central manager or focal consumers to find new providers. For SCT and Self-Evo, the usefulness of the new participants is further limited. In SCT and Self-Evo, consumers can only ask acquaintances for help. However, these new participants are randomly spread in the network, so the consumers, which need new providers for service composition, may not find these new participants.

D. Discussion

In overall terms, according to the experimental results, the proposed approach, Self-Evo, can achieve about 96% of the success rates of the centralised approach MIP and the global information based approach MARL, but uses about 75% less communication and 65% less time than them due to the decentralised features of Self-Evo. This achievement is significant considering that a large amount of communication and time are saved. Such huge communication and time consumption saving is very important in some real world systems, where the energy of each participant is limited\(^9\) and data has to be processed in a timely manner. The proposed approach, Self-Evo, may be computation-intensive, because computation is carried out in each of the five stages of the approach. Such intensive computation may imply a high time consumption in some cases. However, in Self-Evo, the computation is carried out by each participant concurrently in a distributed manner. Thus, the time consumption is not excessive. Moreover, the proposed approach does not require global information. Thus, the time for information acquisition can be saved. Therefore, the time consumption of Self-Evo stays at a relatively low level compared to the other approaches.

Moreover, Self-Evo is better than SCT in various circumstances. This is mainly because Self-Evo allows participants to evolve over time, where only useful acquaintances and services are kept by each participant. Such evolution can significantly reduce communication and time used to find proper providers for service composition.

VI. CONCLUSION AND FUTURE WORK

This paper proposes an agent-based integrated self-evolving service composition approach. This approach is decentralised and self-evolvable. Also, unlike most existing approaches which study only some of the five stages of service composition, the proposed approach consists of five stages of service composition: service discovery, candidate selection, service negotiation, task execution and self-evolution. Such joint optimisation can make the proposed approach more efficient than those which optimise only some stages of service composition.

The proposed approach studies multiple stages of service composition. Each stage has attracted research efforts. Compared to those research efforts, the methods used in the proposed approach for each stage are effective though somewhat simple. Thus, we will focus on the improvement and enhancement of these methods so as to achieve better performance. First, as described in previous sections, there are two limitations in our approach: 1) service presentation is simplified, where for each service type, there is only one candidate service; 2) the approach is relatively computation-intensive in some systems, especially where the computation resource is scarce. These two limitations need to be solved in the future before the proposed approach can be applied in specific systems. Then, as stated in Section V-C, the trust model used in our approach has the cold-start problem which is a common issue of recommender systems in a network environment, especially in a dynamic network environment. Currently, there have been a number of algorithms developed to handle the cold-start problem, which have been summarised in [43]. The development of a new algorithm to address the cold-start issue, which is suitable for the service composition problem, is one of our future studies. Moreover, in the proposed approach, we do not consider specific control logic or workflows, because workflows in service composition depend on specific application domains [5], [20] while our work is carried out in general environments. Thus, when our approach is applied to specific systems, the workflows have to be considered as shown in Section III. Finally, energy consumption was not evaluated in this paper, as it needs to be evaluated within specific networks. The detailed evaluation of energy consumption, however, has to be done when the proposed approach is applied to specific networks in the future.

\(^9\)The proposed approach is developed in a general environment rather than for specific systems or networks. Thus, we did not evaluate the energy consumption in the experiment, as energy consumption needs to be evaluated within specific networks, e.g., WSNs or mobile ad hoc networks. We, however, have evaluated the communication overhead which is an indicator of energy consumption. As communication usually consumes energy, especially in WSNs, low communication overhead implies low energy consumption.
REFERENCES


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