A Formal Approach to Design Optimized Multimedia Service Overlay

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ABSTRACT

Service overlay networks have recently attracted tremendous interests. In this paper, we propose a new integrated framework for specifying services composed of service components running on different service nodes and for executing the services considering efficient utilization of overlay network resources. For a given service description written in an extended Petri net model, our method automatically derives a set of descriptions of service nodes’ behavior which specifies how service nodes on an overlay network collaborate to provide the specified services. The derived descriptions minimize channel utilization, total response time or load of service nodes based on a given cost criterion. The experimental results show that a multimedia service for decorating and transcoding video contents can be well specified and implemented.

Categories and Subject Descriptors
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General Terms
Algorithms, Design

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Overlay Network, Service Composition, Multimedia Service

1. INTRODUCTION

A service overlay network is composed of service nodes where application service components (mainly multimedia service components like filtering, media transcoding and proxy services) are running. Virtual connections are assumed between those service nodes. A service overlay is federation of those service components to provide highly complex and integrated services to its service users. Several algorithms have been presented so far to design service overlay. For example, Xu et al. [13] has proposed a QoS-aware service path mapping algorithm. A service path is a sequential composition of service components (see Fig. 1(a)) and the service path is mapped onto service nodes so that the required QoS and network/computation resource constraints can be satisfied. Wang et al. [11] and Gu et al. [5] have extended the algorithm so that DAGs can be used to specify services. The other recent publications [2, 4, 12, 1, 8, 10] have their own characteristics. Most of them focus on bandwidth provision between service nodes, assuming simple service specifications or traffic models (see Ref. [12] for brief survey).

In this paper, we propose a formal approach to design optimized service overlay networks where a more general service class based on an extended Petri net can be treated. For a given extended Petri net description of service and a given overlay network topology where service nodes are fully-connected with each other, we automatically derive a set of descriptions of service nodes’ behavior which specifies how those service nodes collaborate to provide the required service. Moreover certain costs of the service can be optimized to provide better utilization of overlay network resources even though the service includes multimedia contents processing and transmission. The experimental results, using an example description of video contents decoration/transcoding service and a real network simulator, have shown applicability of our method.

Compared with the existing methods [13, 11, 5, 2, 4, 12, 1, 8, 10], the major contributions of this paper are followings. (i) We can consider service resources such as multimedia contents repositories located on some service nodes. For such a service that includes service resources, we should consider not only simple service path mapping, but also design of protocols for exchanging the contents of those service resources on overlay networks. Fig. 1(b) shows such a service that uses service resources. This provides a video con-
A service overlay is composed of service nodes on which service components are running, and between any pair of service nodes, there exists a virtual channel (i.e., a unicast channel) called an overlay channel. An example of the architecture is shown in Fig. 2. Service users use appropriate services from outside of the service overlay networks. From these service users, the architecture of service overlay networks is completely hidden and it is seen as a single server. However, actually the service nodes have to cooperate to provide the required services under given limitation of network and computing resources.

2. DERIVING BEHAVIOR DESCRIPTION OF SERVICE NODES

A service path example in Ref. [13] by Xu et al.

![Diagram of a service path example](image)

(a) A service path example in Ref. [13] by Xu et al.

![Diagram of service overlay architecture](image)

(b) Our target service.

![Diagram of service overlay architecture](image)

Figure 1: Comparison of service descriptions.

Figure 2: Service overlay architecture.

tents retrieval and transcoding service, using three service resources; a repository $A$ of video contents for PC users, a repository $B$ of low bit-rate video contents for mobile device users and an index table of repositories $A$ and $B$ to process users’ queries of video contents by keywords. Suppose that a mobile device user requests a video content with keywords. This request is processed using the index table. If the index search result indicates that the content is found in repository $B$, the video content is taken from $B$ and is provided to the user. If it indicates that the content is found only in repository $A$, the video content is taken from $A$ and transcoded into low bit-rate video. The transcoded video is stored to repository $B$ for other users and is provided to the requested user. Since these repositories (service resources) are allocated to some service nodes, it is easily understood that executing this service on cooperative multiple service nodes requires a complex protocol between the service nodes. We automatically derive a set of service nodes’ behavior descriptions from a given description of a service with service resources like Fig. 1(b).

(ii) **Overlay network resource utilization** such as bandwidth and computation power of service nodes can be optimized. Of course this is the main issue considered and solved elegantly in the existing work. However, for a more general service class which includes complex service flows with service resources, we need different cost criteria and cost optimization methodology. Moreover, we have conducted realistic experiments, using a real network simulator and a realistic example. In general, theoretical optimization may not be able to capture all the situations in system usage. Thus we have proved that our optimization is really effective in real environments, under various arrival ratios of service requests.

2.1 Inputs to the Algorithm

**[Service Overlay Graph]** We model the architecture as a complete directed graph, where nodes $SN_i (i = 1, 2, \ldots)$ correspond to service nodes and edges correspond to overlay channels between service nodes. This graph is given as an input to the algorithm. Fig. 3(a) shows an example of a service overlay graph.

**[Service Description]** A service description is also given to the algorithm. Fig. 3(b) shows an example of a service description. This example corresponds to the one in Fig. 1(b) and is written in an extended Petri net called a predicate/transition-net ($Pr/T$-net) [3]. We use $Pr/T$-nets for the description of services.

Intuitively, in $Pr/T$-nets, each arc from a place $p$ to a transition $t$ has a form of a linear sum $L(p, t) = \sum_{1 \leq i \leq n} k_i X_i$ of $n$-tuples of variables ($n$ can be an arbitrary integer for each place) where $k_i$ is a non-negative integer and $X_i$ is a tuple of variables like $x_1, x_2, \ldots x_n$. This is called an arc label. Each token in place $p$ is an $n$-tuple of values $C_i = \langle c_{1,i}, c_{2,i}, \ldots c_{n,i} \rangle$, and a set of tokens which can be assigned to arc label $L(p, t)$ is called an assignable set. Moreover, a transition may have a logical formula of variables from the labels on input arcs of $t$, called a condition. The arc from transition $t$ to a place $p'$ also has an arc label which is a form of a linear sum $L(t, p') = \sum_{1 \leq i \leq n} k_i Y_i$ of $n$-tuples of functions where $k_i$ is a non-negative integer and $Y_i$ is a tuple of functions from the variables on the labels of input arcs of $t$. A transition may fire if there exists an assignable set in each input place and the assignment of values to variables by the assignable set satisfies the condition of $t$. If $t$ fires, new sets of tokens are generated and put into the output places according to the labels on the output arcs of $t$. Note that the data type of token values in a place and the data type of labels of the arcs from/to the place must be the same.

For modeling services, we define the following class of $Pr/T$-nets. Places are classified into two types, (i) **resource places** and (ii) **service flow places**. Resource places represent service resources such as databases. The number of tokens in the resource places never increases or decreases, i.e., the transitions from the resource places are represented as self-
loops where the contents of the resources may be changed by executing the transitions from the resource places. In Fig. 3(b), places P5, P6 and P7 are such resource places. The other places are service flow places. By removing the resource places and their self-loop arcs, the service flow places and the transitions form a partial Pr/T-net which models the execution flow of the service. It is called a service flow net. The resource places and associated transitions are used to represent the utilization of service resources in the service flow net. To model multiple users who use the same service, multiple tokens with different values can be given in the service flow net. This class of Pr/T-net considerably extends the expressive power to describe service requirements, compared with the existing work (most of the work considers only sequential services or services represented as DAGs).

In Fig. 3(b), service flows are modeled by service flow places (denoted as white circles) and transitions, and video repositories and their index are modeled by resource places (denoted as meshed circles). Inside the service flow places, there may exist multiple tokens to distinguish different users’ requests. For example, two tokens in place P1 represent two service requests. Pr/T-nets can handle such multiple flows in a single net, thus it is better to be used to write a system which handles multiple users. Similarly, resource places may have tokens inside, which represent the entities of resources. Moreover, inside the transitions (rectangles), conditions may be specified which use the variables from the arc labels of service flow places. Using the condition, we can describe conditional branches or iterations. For example, service flow place P2 has multiple output transitions that have conditions on the variable “repo” from the labels of the input arcs from P2 to these transitions.

[Allocation of Places to Service Nodes] The algorithm requires all the places of the given service description to be allocated to the service nodes. For example, in Fig. 3(a), places P1 to P7 are allocated to service nodes SN1 to SN4. overlays will be discussed in Section 3. An allocation may be designed manually by developers or an optimized allocation that minimizes certain costs of the service can be obtained using the Integer Linear Programming (ILP) technique described in Section 3.

2.2 Output

[Description of Service Nodes’ Behavior] We assume that places P1, P2 and P5 are located on service nodes SN1, SN2 and SN3 respectively, as shown in Fig. 3(a). Assuming this allocation of places, we see, in Fig. 3(c), a part of behavior of service nodes that corresponds to transition T1 to understand service nodes’ behavior descriptions.

Each service node has its own behavior description written in a Pr/T-net. Between the Pr/T-nets, we introduce places for modeling asynchronous and reliable communication on overlay channels called communication places. We assume that two communication places with a common name “T.Xij” (T represents the corresponding transition and X = α or X = β, explained later) in the Pr/T-nets of two different service nodes SNi and SNj represent message passing from service node SNi to service node SNj through the overlay channel between them. If a token is put on “T.Xij” at service node SNi, the token is eventually removed and put it onto “T.Xij” at service node SNj. Note that the prefix “T” means that these communication places are used with respect to the execution of transition T of the service description. Communication places are represented as dotted circles in the following figures.

The transition T1 is executed as follows. At first, service node SN1 takes a token (an assignable set) from P1 (user request spool) by firing of transition T1.start and assigns it to the tuple of variables “(keys,target)”. If the assignment satisfies the condition of T1, then these values are sent to SN2 and SN3 via communication places T1.α12 and T1.α11, respectively, since SN2 needs both values to generate a token to P2 and SN3 needs the value of “keys” to generate a token to P5. In response, SN3 takes a token from P5 by firing of T1.read. Since the value of token taken from P5 is used to generate a token to P2, the value of “idx” is sent to SN2 via T1.β32. Using these values sent from SN1 and SN3, SN2 generates a token to P2 by firing...
of $T1\text{.commit}$. Similarly, $SN3$ generates a token to $P5$ by firing of $T1\text{.commit}$. Note that $SN3$ sends an empty value $\phi$ to $SN1$ via $T1_{\beta_{31}}$ to let $SN1$ know that $SN3$ could obtain a token from $P5$. After knowing it, $SN1$ is ready to accept the next token. For this mutual exclusion control purpose, we introduce two places with black dots (empty value tokens $\phi$) in $SN1$ and $SN3$.

Tokens carried through $T_{\alpha_{ij}}$ and $T_{\beta_{jk}}$ are called $\alpha$-messages and $\beta$-messages, respectively. An $\alpha$-message through $T_{\alpha_{ij}}$ is used to carry values that will be used to generate token values at the receiver service node $SNj$ as well as to let $SNj$ obtain assignable sets from the input places of $T$ allocated to $SNj$. A $\beta$-message through $T_{\beta_{jk}}$ is sent in response to reception of the $\alpha$-message, and is used to carry the obtained values that will be used to generate tokens at $SNk$.

2.3 Algorithm

The basic idea of the algorithm is inspired by our protocol synthesis technique in Ref. [14]. For each transition $t$ of the given service description, depending on a given allocation of places, we identify the set of service nodes called reading service nodes which have at least one input place of $t$, and also the set of service nodes called writing service nodes which have at least one output place of $t$. Then we select one of the reading service nodes as the primary service node. Afterward, in order to execute $t$ over multiple service nodes, we apply to transition $t$ the derivation algorithm based on a protocol called a transition execution (TE) protocol that determines how the behavior of $t$ is simulated by service nodes. By decomposing every transition of service description based on the TE protocol, we finally obtain the set of behavior descriptions of service nodes.

3. FOR OPTIMIZED SERVICE OVERLAY

The algorithm described in the previous section assumes that an allocation of places is given. In this section, we determine an optimal allocation of places to service nodes to derive an optimized service overlay. The optimal allocation of places leads to the optimized service overlay where its cost is minimized. The cost can be one of maximum channel utilization, maximum response time and maximum load of service nodes. If we choose one of these costs to be minimized according to application domains, we may give some constraints on the other metrics. Using the optimal allocation of places, we can derive an optimized service overlay according to the algorithm in the previous section.

We derive an optimal allocation of places using an Integer Linear Programming (ILP) problem. We introduce the following 0-1 integer (boolean) variables: (i) $\alpha^t_{i,j}[v]$ : one if an $\alpha$-message is sent from $SNi$ to $SNj$ and carries the value of a variable $v$ on the execution of transition $t$ (zero otherwise), (ii) $\beta^t_{j,k}[v]$ : one if a $\beta$-message is sent from $SNi$ to $SNj$ and carries the value of a variable $v$ on the execution of transition $t$ (zero otherwise), and (iii) $al^p_{i,j}$ : one if place $p$ is allocated to $SNj$ (zero otherwise).

The followings are the cost criteria. (i) Maximum channel utilization. Since these services deal with large-sized (e.g., orders of giga-bytes) resources transmitted between service nodes, it is very important to prevent those large-sized resources from being transferred at the same time through a single or a few overlay channel(s) with poor bandwidth. Here, we try to identify a set of transition instances that can be executed in parallel, for example, by maximum occurrence distance analysis [7]. Moreover, if two independent users execute different transitions at almost the same timing, those transitions can be also regarded as parallelized transitions. Using those techniques and service request patterns of users, we can identify multi-sets of transitions that may be executed in parallel. Let $MT$ denote a set of those potential multi-sets of transitions. Here, for each overlay channel $(i, j)$, we define the maximum channel utilization of $(i, j)$, denoted as $util_{i,j}$, as the ratio of the maximum amount of data to be transmitted through the channel $(i, j)$ at the same time, to the capacity of the channel. $util_{i,j}$ can be defined as follows.

$$util_{i,j} = \max_{MT} \left\{ \frac{\sum_{t \in MT} \sum_{v \in var(t)} SZ(v) \ast (\alpha^t_{i,j}[v] + \beta^t_{j,k}[v])}{BW(i, j)} \right\}$$

Here, $BW(i, j)$ denotes the capacity of overlay channel $(i, j)$, $SZ(v)$ the size of a variable $v$, and $var(t)$ the set of variables that appear in the labels of the input arcs attached to the transition $t$. We may want to minimize $\max_{(i,j) \in E} \{ util_{i,j} \}$, denoted as $util$, the maximum of the maximum channel utilization of all the channels to avoid concentration of bandwidth utilization where $E$ denotes the set of the overlay channels. (ii) Maximum response time. The maximum response time of the service for a user, is the cumulative execution time of the transitions on the "longest path" of the service. According to the derivation algorithm, the execution time of transition $t$ can be defined as the maximum of the transmission time of a sequence of an $\alpha$-message from $SNi$ to $SNj$ and a $\beta$-message from $SNj$ to $SNk$ plus the maximum execution time of functions that appear in the labels of the output arcs from $t$ to the places of $t$ allocated to $SNk$. Let $TS(t, p)$ denote the sum of the task sizes of functions attached to the arc $(t, p)$ and $PW(j)$ denote the size of tasks which $SNj$ can process per unit of time. The maximum execution time of $t$, denoted as $exec^t$, can be defined as follows.

$$exec^t = \max_{(i,j) \in E} \left\{ \frac{\sum_{v \in var(t)} SZ(v) \ast (\alpha^t_{i,j}[v])}{BW(i, j)} + \frac{\sum_{v \in var(t)} SZ(v) \ast (\beta^t_{j,k}[v])}{BW(j, k)} + \max_{p \in \{t\}} \{ TS(t, p) \ast al^p_{i,j} \} \right\}$$

where $\{t\}$ denotes the set of output places of transition $t$. Here, let $LS$ denote the set of all the potential longest paths (transition sequences) of a given service. We may want to minimize $resp = \max_{LS} \{ \sum_{t \in LS} exec^t \}$, the maximum response time of the service. (iii) Maximum load of service nodes. The maximum load of a service node $SNj$, say $load_{j}$, can be defined using $MT$, which was used in the definition of maximum channel utilization. $load_{j}$ is given as follows.

$$load_{j} = \max_{MT} \left\{ \sum_{t \in MT} \sum_{p \in \{t\}} \frac{TS(t, p)}{PW(j)} \ast al^p_{i,j} \right\}$$

We may want to minimize $load = \max_{S \in LS} \{ load_{j} \}$, the maximum load of service nodes where $S$ denotes the set of service nodes.

Here, according to application domains, we can choose one of the above metrics to be optimized, giving certain
constraints on the others if necessary. However, due to limitation of space, hereafter we only present the ILP problem that minimizes maximum channel utilization where certain constraints are given to the maximum response time and maximum load of service nodes.

The following is the objective function.

$$\min util$$ \hspace{1cm} (1)

From the definition of “max” functions, the following constraints are necessary.

$$\forall (i,j) \in E; \; util \geq util_{i,j}$$ \hspace{1cm} (2)

We may want to set certain thresholds of the maximum load \(load_j\) of each service node \(SN_j\) and the maximum response time \(resp\). Let \(LTH(j)\) and \(RTH\) denote the thresholds of \(load_j\) and \(resp\), respectively. We obtain the following constraints.

$$\forall j \in S; \; load_j \leq LTH(j)$$ \hspace{1cm} (3)

$$resp \leq RTH$$ \hspace{1cm} (4)

In addition, we need the following constraints some of which come from the definitions of variables and others from the algorithm. \(prit_i\) is a 0-1 integer variable and the value is one iff \(SN_i\) is the primary service node in the execution of transition \(t\) of the service. \(Ps\) is the set of service flow places.

$$\forall (i,j) \in E; \forall t \in T; \forall p \in \bullet; \forall p' \in t\bullet, \forall v \in var(L(p,t)) \cap var(L(t,p'));$$

$$\alpha_{i,j}[v] \geq alc_{i,j} + alc_{i,j}' + prit_i - 2 \hspace{1cm} (5)$$

$$\beta_{i,j}[v] \geq alc_{i,j} + alc_{i,j}' - prit_i - 1 \hspace{1cm} (6)$$

$$\forall (i,j) \in E; \forall t \in T; \forall v \in var(t); \; \alpha_{i,j}[v] + \beta_{i,j}[v] \leq 1 \hspace{1cm} (7)$$

$$\forall p \in P; \sum_j alc_{i,j} = 1 \hspace{1cm} (8)$$

$$\forall t \in T; \sum_j prit_j = 1 \hspace{1cm} (9)$$

$$\forall j \in S; \forall t \in T; \forall p \in \bullet \cap Ps;$$

$$alc_{i,j} = prit_j \hspace{1cm} \text{iff} \; |p \bullet| > 1$$

$$alc_{i,j} \geq prit_j \hspace{1cm} \text{otherwise} \hspace{1cm} (10)$$

We note that if the ILP problem is hard to obtain an optimal solution within realistic computation time, several techniques can be used such as \(\varepsilon\)-approximation or linear relaxation.

### 4. TOOL SUPPORT, APPLICATION EXAMPLE AND EXPERIMENTAL RESULTS

[Toolset] We have developed a toolset in Perl which works together with a graphical tool “CPNtools”. In the toolset, we first describe the service using CPNtools. Second, our toolset parses the given description of service in the CPNtools format (described in XML with DTD) using XML Parser, and generates the corresponding ILP model presented in Section 3. Third, we use the tool CPLEX to solve the ILP problem and determine the optimal allocation of places. Fourth, using the optimal allocation of places, our Perl toolset generates the corresponding set of service node behavior descriptions.

[Application Example] Here, we consider an automated video decoration and transcoding service on overlay networks as an application example. In this service, a given movie in DV format is decorated by opening and ending movies, and the decorated movie file is de-multiplexed into video and audio files. The quality of the video is adjusted depending on capabilities of users’ devices and then encoded into appropriate formats, such as MPEG2 and MPEG4. The description is given in Fig. 4.

[Experimental Results] Since our optimization is based on estimated arrival ratios of user requests (recall that a set \(MT\) of parallelized transitions used in the definition of cost functions depends on arrival ratios of user requests), we need to validate that the values of cost functions are really improved by our optimization at any arrival ratio in realistic network environments.

To do so, we have developed a simulator toolset by letting two software tools collaborate with each other, (i) a high-level Petri net simulator called Maria[6] and (ii) a real network simulator GTNetS[9]. Maria executes the descriptions of service node behavior which are derived by our Perl toolset explained at the beginning of this section. If it finds a token in a communication place, it tells the transmission requirement to GTNetS with the size of token(s). GTNetS simulates a TCP-based overlay network and starts generating traffic according to the transmission requirement between two service nodes at packet level. When it finishes the transmission, GTNetS tells the end of transmission to Maria. Maria and GTNetS continue their operations cooperatively until Maria finds that no executable transitions is left.
From the given service and five service nodes, we have derived, using our Perl toolset, three different sets of service node behavior descriptions optimized using three cost functions introduced in Section 3: (i) maximum channel utilization, (ii) maximum response time, and (iii) maximum load of service nodes. We have assumed 0.01 arrival ratio of service user requests to determine MTF in the cost functions. Then we have measured, using our simulator toolset, the average values of those metrics, varying the arrival ratios of service users’ requests. We have given random values between 70 Mbps and 130 Mbps as the physical link capacity. We have used TCP as the overlay channels, and set each overlay channel capacity to the minimum capacity of links on the channel. We have set the sizes of contents as follows; Raw video file has 5 Gbytes and its corresponding formats are 4 Gbytes (DV), 1 Gbyte (MPEG2) and 128 Mbytes (MPEG-4). In a multiplexed stream, we assume that the ratio of video:audio is 9:1.

For comparison, we have derived additional two sets of service node behavior descriptions for each cost function. (i) “random allocation” where video contents are allocated to service nodes with enough computation power and communication capacities and then other service components are allocated randomly. We obtain the best solution from 10 trials. (ii) “manual allocation” which is a manually thought-out allocation where we repeat trial and error so that sequences of service components can be executed without communicating with other service nodes as long as possible.

Fig. 5 shows the results. We note that the definition of the maximum channel utilization in Fig. 5(a) is different from the one in Section 3. We have measured in Fig. 5(a) the ratio of the bandwidth that is actually used, to the capacity of the channel, since it is a more natural metric to represent network performance. We can see that even under high arrival ratios of user requests, all the costs of the optimized service have the advantage over the random/manual allocations. In other words, even though the optimization is done using some (high) arrival ratio of user requests, the result under any ratio shows our advantage. The time for deriving optimized allocations was a few minutes in most cases.

5. CONCLUSION

In this paper, we have proposed an approach to design optimized service overlay networks. The introduction and evaluation of more adaptive QoS control mechanism depending on fluctuation of usable bandwidth of the overlay channels is part of our future work.

6. REFERENCES