A Cloud-Edge Computing Framework for Cyber-Physical-Social Services

Xiaokang Wang, Laurence T. Yang, Xia Xie, Jirong Jin, and M. Jamal Deen

The authors present a tensor-based cloud-edge computing framework that mainly includes the cloud and edge planes. The cloud plane is used to process large-scale, long-term, global data, which can be used to obtain decision-making information such as the feature, law, or rule sets. The edge plane is used to process small-scale, short-term, local data, which is used to present the real-time situation.

ABSTRACT

Cyber-physical-social systems (CPSSs) represent an emerging paradigm encompassing the cyber world, physical world and social world. One of the main purposes of CPSSs is to provide high-quality, proactive, and personalized services for humans. For CPSSs to realize this purpose, a novel services framework is needed. In this article, we present a tensor-based cloud-edge computing framework that mainly includes the cloud and edge planes. The cloud plane is used to process large-scale, long-term, global data, which can be used to obtain decision making information such as the feature, law, or rule sets. The edge plane is used to process small-scale, short-term, local data, which is used to present the real-time situation. Also, personalized services will be directly provided for humans by the edge plane according to the obtained feature, law, or rule sets and the local high-quality data obtained in the edge plane. Then a tensor-based services model is proposed to match the requirement of users in the local CPSS. Finally, a case study about CPSS services is proposed to demonstrate the application features of the proposed framework.

INTRODUCTION

Over the past few decades, the rapid development of the Internet of Things (IoT), also referred as cyber-physical systems (CPSs), has accelerated the digital revolution and enhanced intelligent human living environments. As an extension of CPS (IoT), cyber-physical-social systems (CPSSs), including the cyber world, physical world, and social world, are proliferating in all aspects of our daily lives. One of the main purposes of CPSSs is to enhance living environments by providing high-quality proactive and personalized services to humans [1–3].

In CPSSs, large-scale data about our daily lives are continually generated from three worlds. Flowing around the three worlds and recording all aspects of our daily lives, data, as the common element, were selected as the starting point of our research [1]. However, large-scale data collected from CPSSs are often redundant, complex, noisy, and low-quality, resulting in unprecedented challenges for providing CPSS services [1]. Furthermore, to provide high-quality services in CPSSs, a comprehensive analysis about big data based on cloud computing is essential.

Cloud computing, with its powerful computational potential, has triggered enormous attention for CPSS big data processing [1, 4]. However, cloud computing has faced increasing computational demands because of the exponential growth of big data, including both large-scale, long-term, global data and small-scale, short-term, local data. Also, the huge computational tasks on the cloud bring others challenging issues related to cost, energy consumption, and quality of the provided services. With the computational capability inherent in many smart devices such as smartphones, innovative research in this challenging area has been motivated by the rise of spatial edge computing [5]. Therefore, a novel computing framework to systematically and comprehensively process those data for providing CPSS services is required.

For example, thousands of cameras have been installed to monitor the traffic conditions in smart cities [6]. With these cameras, large-scale, complex, long-term, global data about city traffic will be collected over a long period. Cloud computing can be used to process the collected data and to obtain the characteristics or rules of the traffic congestion. Then smart devices around cameras can be used to estimate whether the traffic congestion happens according to the obtained characteristics or rules of the traffic congestion and the real-time traffic data. Figure 1 shows the relationship among CPSSs, cloud computing, edge computing, and services. For providing services in this manner, several challenges, including the following three questions, must be addressed.

1. How can we effectively process the big data to obtain high-quality data?
2. How can we analyze the users' corresponding data from the perspective of multi-order attributes?
3. How can we match the requirements, hobbies, and habits according to users' local environments?

In this article, we present a cloud-edge computing framework for providing CPSS services, and the main contributions are as follows. First, we present a novel cloud-edge computing framework for efficiently integrating cloud computing and edge computing. Second, we

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propose two kinds of tensor integration methods, including the multi-order outer product and multi-order integration strategy, to combine several attributes together. Third, we propose a tensor-based services model used to match the requirements, hobbies, and habits of users. Fourth, we use the multi-order distributed incremental method in this framework to improve the processing efficiency. To describe these contributions, this article is divided into five sections. We provide background information and motivation for our work. We briefly summarize related works including CPSSs, big data, tensor, cloud computing, and edge computing. An overview of the framework and a tensor-based services model are provided. A case study about CPSS services matching is discussed. Finally, conclusions are given.

Related Work

In this section, a concise review of the state of the art in CPSSs, big data, tensor and its high-order singular value decomposition (HOSVD), cloud computing, and edge computing is provided.

Cyber-Physical-Social Systems: Integrating the cyber, physical, and social worlds, CPSSs are considered as a hybrid world where community detection among humans, objects, and cyber actors can be obtained [1]. Many publications about object identification in CPSSs are available to precisely recognize users [7, 8], understand their requirements under different conditions, and even appropriately render high-quality services [8]. However, matching methods, referred to as the basis of precise identification of an object in CPSSs, have been studied and used in many applications such as human motion recognition [9], health [10], human face identification [11], and smart home [6, 12, 13]. Additionally, CPSS big data, as the research starting point of CPSSs, are typically high-order, complex, large-scale, redundant, and noisy. Therefore, systematic methods for representation, integration, and processing of CPSS big data are needed.

Big Data, Tensor, and HOSVD: With the 4V characteristics — volume, variety, veracity, and velocity — CPSS big data bring unprecedented challenges using existing computational methods and models [14]. The tensor, as an extension of a matrix in high-order space, was proven to be an appropriate, reasonable big data representation method [15]. HOSVD, one of the main tensor decomposition methods, was used to process big data for denoising and removing redundant data [1, 15]. To improve the computational efficiency of HOSVD, a tree-based multi-order distributed HOSVD (MDHOSVD), with its incremental computing method in which a tensor can be divided or increased along several or even all orders at the same time, was discussed in [1].

Cloud Computing and Edge Computing: The emergence of cloud computing and its potential to provide computation and storage capabilities for services was propelled by the availability of powerful processing hardware and software. Edge computing is emerging as a novel computational paradigm and is a result of the rapid advances in IoT [5]. Currently, smart devices such as smartphones, laptops, and embedded devices are significantly changing the way we conduct our daily activities, and these smart devices are endowed with increasingly powerful computational capacities. In [5], a detailed survey about mobile edge computing was presented. Also, several applications and key technologies of mobile edge computing were discussed.

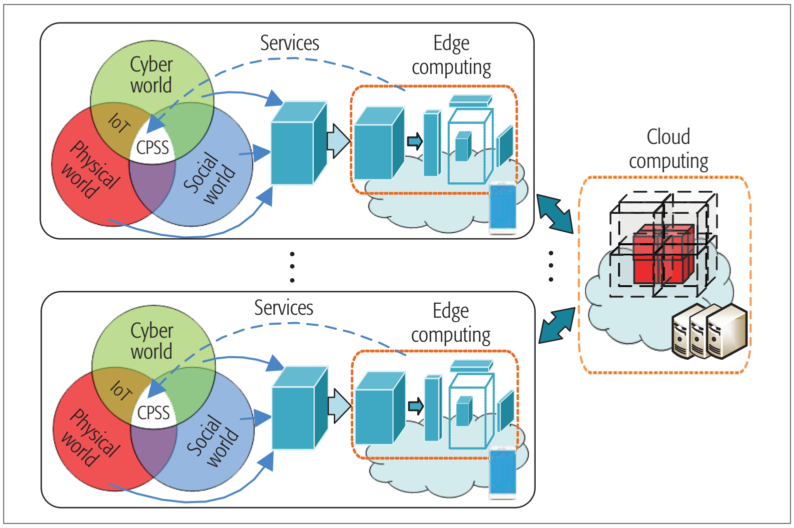

Figure 1. Relationship among a CPSS, cloud computing, edge computing and services.

Overview of the Cloud-Edge Computing Framework

In Fig. 2, as an extension of our previous work in [1], a cloud-edge computing framework including the edge plane, cloud plane, and application plane was studied. Here, the three parts — edge plane, cloud plane, and application plane — with relevant examples are given. The functions of these three parts are now described.

Edge Plane: In this plane, two main tasks of data representation and its initial cleaning, matching, and services providing are performed. A tensor model with its HOSVD is used to represent collected data and extract corresponding high-quality data. Also, matching and services will be implemented and provided directly to users, according to these high-quality data and the obtained feature, law, or rule sets from the cloud plane.

Cloud Plane: In the cloud plane, two important tasks — global data integration and processing, and the acquisition of feature, law, or rule sets — are accomplished. Two methods are used to implement data integration. Also, MDHOSVD is used to obtain the high-quality data of the global data. Furthermore, corresponding methods are implemented to obtain the feature, law, or rule sets in this plane.

Application Plane: In the application plane, high-quality data, as well as the feature, law, or rule sets, are applied for some applications.

The three planes in Fig. 2 complement each other and are used to construct the framework, which forms the basis for CPSS applications and services. In the following subsections, we provide brief descriptions of each plane. In this article, we mainly pay attention to the interconnected operations between the cloud plane and

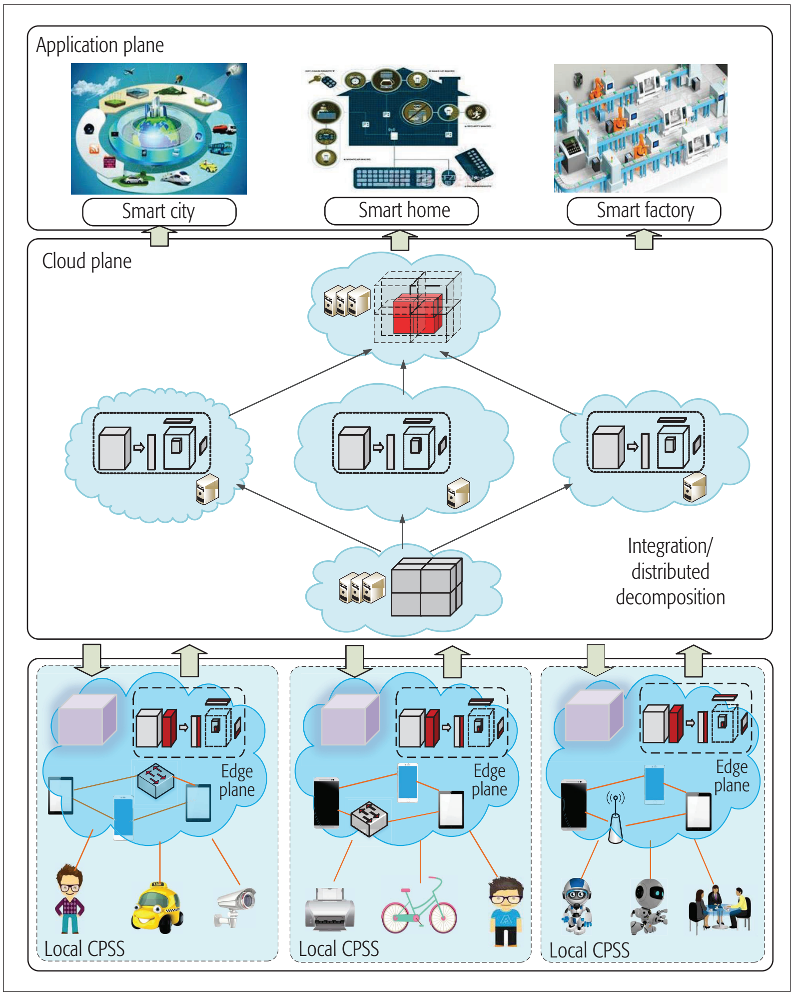

Figure 2. Cloud-edge computing framework.

the edge plane to provide high-quality services for humans.

Data Representation and Reduction in the Edge Plane

In this article, a tensor, a data representation tool, is used to represent the various data collected in the edge plane. In our previous work [15], a tensor-based big data unified representation method was used to represent unstructured data (e.g., video clips), semi-structured data (e.g., XML documents), and structured data (e.g. GPS). Also, HOSVD is employed to process the collected data for obtaining high-quality data. For example, the HOSVD results of an Nth-order tensor $\mathcal{A}$ are computed as

$$\mathcal{S} = \mathcal{A} \times_1 U_1^T \times {}_2 U_2^T \cdots \times_n U_n^T \cdots \times_N U_N^T, \qquad (1)$$

where, $\mathcal{S}$ is the core tensor and matrix U_n, $1 \leq n \leq N$ is the left singular matrix of the nth order. The core tensor $\mathcal{S}$ and matrix U_n, $1 \leq n \leq N$ as well as its approximate tensor are referred to as the high-quality data of tensor $\mathcal{A}$ [1, 15].

In every local CPSS, data are continuously generated from the perspective of multi-attributes, represented as the multi-order tensor streaming, which will be processed by multi-order incremental HOSVD (MIHOSVD) as discussed in [1]. Otherwise, in local CPSSs, some simple computational tasks such as matching or ranking will be implemented on the edge plane.

Tensors Integration and Processing in Cloud Plane

In this part, two main tasks — integration and processing of tensors — are discussed. Two methods of tensors integration are proposed to integrate several associated attributes to make sure that they can be analyzed together. Then MDHOSVD is employed to process the integrated tensor and to improve the computational efficiency.

Multi-Order Outer Product: To provide services, the associated collected data should be analyzed from the perspective of multi-attributes to extract the useful information such as the multi-order face feature or multi-order gait feature. Although a tensor is used to represent the multi-attributes data, there is still a challenging question because it cannot completely represent the associated data such as the tensor of face data or that of the same person's gait data. Therefore, a multi-order outer product is proposed to integrate different tensors, which have the same attributes such as persons to uniformly represent these multi-attributes data together.

As shown in Fig. 3, an Nth-order tensor $\mathcal{A}$ and an Mth-order tensor $\mathcal{B}$ have k common orders $I_{n_1} = J_{n_1}$, $I_{n_2} = J_{n_2}$, $\cdots$, $I_{n_k} = J_{n_k}$, referred to as targeted orders. A multi-order outer product to integrate these two tensors and obtain an $(N + M - k)$th-order result tensor $\mathcal{C}$, which has all orders from these two tensors that do not have redundant orders, is performed as follows.

1. Tensor $\mathcal{A}$ is fully divided along all k common orders to obtain a series of sub-tensors $\mathcal{A}^{(i_{n_1}, i_{n_2}, \cdots, i_{n_k})}$, $1 \leq i_{n_k} \leq I_{n_k}$, where the superscript $(i_{n_1}, i_{n_2}, \cdots, i_{n_k})$ is the coordinate of this sub-tensor in tensor $\mathcal{A}$. In the same way, tensor $\mathcal{B}$ is also fully divided into a series of sub-tensors along all the k common orders.
2. Then a sub-tensor $\mathcal{C}^{(i_{n_1}, i_{n_2}, \cdots, i_{n_k})}$ will be computed by the outer product between sub-tensor $\mathcal{A}^{(i_{n_1}, i_{n_2}, \cdots, i_{n_k})}$ and sub-tensor $\mathcal{B}^{(i_{n_1}, i_{n_2}, \cdots, i_{n_k})}$.
3. By reorganizing sub-tensors $\mathcal{C}^{(i_{n_1}, i_{n_2}, \cdots, i_{n_k})}$ according to their coordinates, a resultant tensor $\mathcal{C}$ is obtained. $\mathcal{C}$ has all the orders of both tensors $\mathcal{A}$ and $\mathcal{B}$.

Multi-Order Integration Strategy: The multi-order integration strategy is proposed to integrate the k targeted orders into a hybrid order I_H in a certain tensor such as tensor $\mathcal{A}$. Then a hybrid tensor $\mathcal{A}^h$ will be obtained, in which the dimensionality of the hybrid order is equal to $I_H = I_{n_1} \times I_{n_2} \times \cdots \times I_{n_k}$.

After integrating tensors, we get a large-scale hybrid tensor in the cloud plane. Currently, we prefer to utilize MDHOSVD to process this large-scale hybrid tensor, thus obtaining its high-quality data set.

MDHSOVD: The purpose of MDHOSVD is to realize the HOSVD result of the large-scale tensor according to that of its sub-tensors. Taking the MDHOSVD of an Nth-order $\mathcal{A}$ as an example to explain its computational process, it can be abstracted into a tree with $(N + 1)$ layers and summarized as follows.

1. Each sub-tensor will be sent to a node of the $(N + 1)$th layer, where each sub-tensor will be unfolded along N orders, respectively. Then singular value decomposition will be implemented on these N unfolding matrices in each employed node.

2. Next, the computational result of each unfolding matrix will be sent to a node of the Nth layer. From this step, integrate the sub-tensors along the jth order in the jth layer, where j is selected from N to 1. Then the task is to obtain the singular value decomposition of each unfolding matrix of the integrated tensor according to that of each sub-tensor. After realizing this computational task in the first layer, we will get the left singular value matrix U_i, $1 \le i \le N$. Then the HOSVD of tensor $\mathcal{A}$ will be obtained according to Eq. 1.

A Tensor-Based Services Model

Based on the cloud-edge computing framework, a tensor-based services model is proposed in this article. To clearly express this model, the ServiceTensor is first proposed.

- **ServiceTensor**: The ServiceTensor is used to represent the requirements, interests, and habits in scenarios of local CPSSs. The ServiceTensor of a user is represented as an Nth-order tensor $\mathcal{A} \in R^{I_1 \times I_2 \times \cdots I_{n_1} \times I_{n_2} \cdots \times I_{n_k} \cdots \times I_N}$, where requirements, interests, and habits are represented by k targeted orders under a scenario of a local CPSS represented by the combination of the left $(N - k)$ untargeted attributes.

Next, the working process of the tensor-based services model is summarized as follows.

1. In the cloud plane, ServiceTensor $\mathcal{A}$ will be established by a learning method such as deep learning, according to the long-term, large-scale global data.
2. When a user gets into a local CPSS, sensing devices will collect his/her data in a real-time scenario with multi-attributes. Normally, tensor $\mathcal{B} \in R^{I_1 \times I_2 \times \cdots I_{n_1-1} \times I_{n_k+1} \cdots \times I_N}$ is used to represent the current scenario, in which a certain order is used to represent an attribute. Also, the edge plane process tensor $\mathcal{B}$ by HOSVD is used to obtain its high-quality data. Then the high-quality data of tensor $\mathcal{B}$ will be sent to the cloud plane, where a tensor equation

$$\mathcal{A} \times_{I_{n_1} I_{n_2} \cdots I_{n_k}}^{I_{n_1} I_{n_2} \cdots I_{n_k}} \mathcal{X} = \mathcal{B}, \tag{2}$$

has to be solved to obtain the requirements, interests and habits tensor $\mathcal{X}$. The operation

$$\times_{I_{n_1} I_{n_2} \cdots I_{n_k}}^{I_{n_1} I_{n_2} \cdots I_{n_k}}$$

means multi-order product on the k targeted orders. The main steps of solving this equation are summarized as follows.

a. For tensor $\mathcal{A}$ in Eq. 2, integrate the k targeted orders into a hybrid order I_H and obtain a hybrid tensor $\mathcal{A}^h$.

b. Next, multi-order products on the untargeted orders by $\mathcal{A}^h$ on both tensors $\mathcal{A}^h$ and $\mathcal{B}$ are carried out. After this, we can change the high-order tensor of Eq. 2 into a matrix equation.

c. For the matrix equation in b, we can use the solution of the matrix equation to get the corresponding answer vector. According to the "multi-order integration strategy" and corresponding answer vector, we will get the kth-order tensor $\mathcal{X}$.

3. In the edge plane, fully divide the approximate tensor according to all the untargeted orders. Then we will get a series of sub-tensors $\mathcal{A}_m$. According to [9], a similar matching ratio α_m can also be used to estimate the requirements. Then we will queue a series of matching ratios α_m from large to small values. The requirement tensor $\mathcal{A}_m$ corresponding to the maximal matching ratio is the goal we seek.
4. Finally, the edge plane will inform some smart devices such as smartphones or even a robot to provide services, according to the requirement tensor $\mathcal{A}_m$.

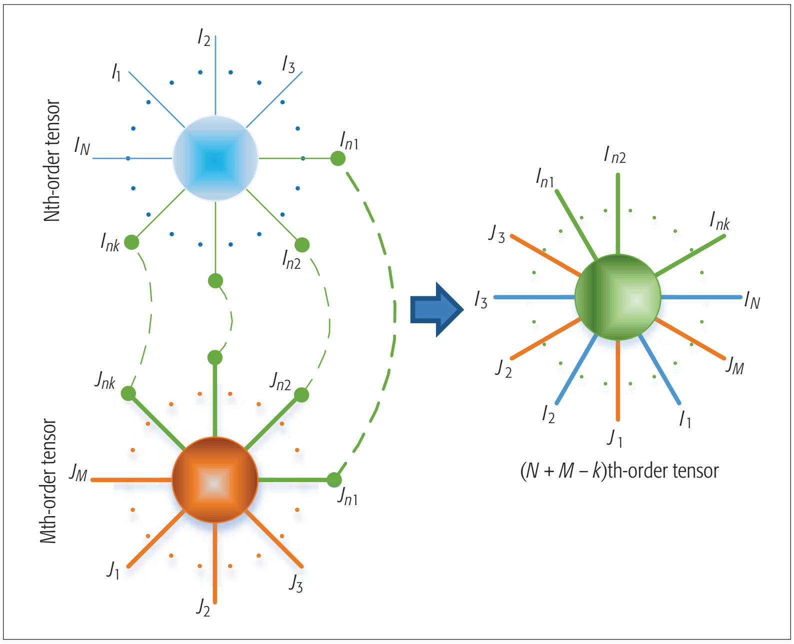

Figure 3. Tensors integration.

Case Study

In this section, a case study about the proactive and personalized services provision is used to illustrate the working process of the tensor-based services model on the cloud-edge computing framework. As shown in Fig. 4, five users, whose ServiceTensors $\mathcal{A}_0$ have been prepared by the cloud plane, get into a local CPSS.

Here, for convenience, we suppose that the corresponding requirements are based on the combination of their face data and gait data in different scenarios. With a similar representation manner to [9, 11], two 4th-order tensors $\mathcal{F} \in R^{I_1 \times I_2 \times I_3 \times I_4}$ and $\mathcal{T} \in R^{J_1 \times J_2 \times J_3 \times J_4}$ are used to represent facial data and gait data, respectively, where $I_1 = J_1 = 5$ means five users; $I_2 = 7$ means seven different expressions including speaking, anger, sadness, shouting, peaceful, happy, and hurried; I_3 and I_4 are used to represent the height and width of the face photo; J_2 means the angle between walking direction and the camera (including 15° to left, 30° to left, 60° to left, 15° to right, 30° to right, 60° to right); J_3 means the number of frames in a walking cycle (also the number of photos in a cycle); and $J_4 = 7$ means the selected joint angle including the front shoulder joint angle, back

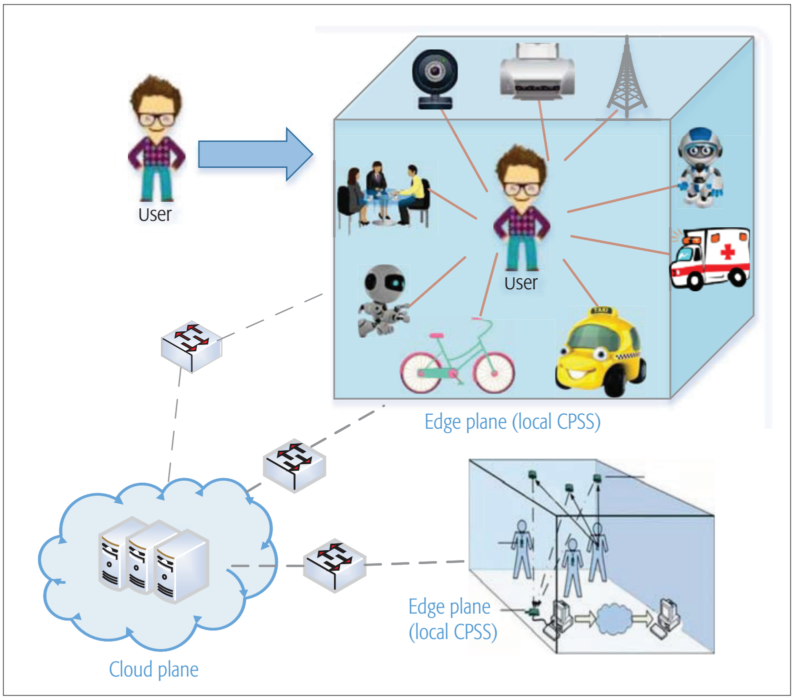

Figure 4. A case study of tensor-based services.

shoulder joint angle, joint angle between two legs, and joint angle of two knees and two ankles.

Also, these requirements were prepared by learning methods in the cloud plane and represented by tensor $\mathcal{A}_0 \in R^{I_1 \times I_2 \times I_3 \times I_4 \times J_2 \times J_3 \times J_4}$. For example, when the third user (i_1 = 3) feels very tired and wants to sleep, he will be very sad (i_2 = 3) and the walking direction is 15° to the right (j_2 = 4). When the fourth user (i_1 = 4) is going to a restaurant for dinner, she is always talking with her friend (i_2 = 1), and the walking direction is 60° to the left (j_2 = 3). When the fourth user (i_1 = 4) is hurrying (i_2 = 7) and his walking direction is 60° to the right (j_2 = 6), he is very busy and needs a vehicle such as a taxi or a shared bicycle.

Now, we take the matching in three scenarios to demonstrate the performance of the tensor-based service model. Suppose a user gets into a local CPSS, and her corresponding data, including the face data $\mathcal{F}^i \in R^{I_1^i \times I_2^i \times I_3 \times I_4}$, $1 \le i \le 3$, $I_1^i = I_2^i = 1$ and gait data $\mathcal{T}^i \in R^{I_1^i \times J_2^i \times J_3 \times J_4}$, $1 \le i \le 3$, $I_1^i = J_2^i = 1$ in a certain scenario, are collected. Then the hybrid tensor $\mathcal{B}^i \in R^{I_1^i \times I_2^i \times I_3 \times I_4 \times J_2^i \times J_3 \times J_4}$, $1 \le i \le 3$, $I_1^i = I_2^i = J_2^i = 1$ is obtained by integrating tensors $\mathcal{F}^i$ and $\mathcal{T}^i$ using the multi-order outer product. $\mathcal{A}_0^j \in R^{I_1^j \times I_2 \times I_3 \times I_4 \times J_2 \times J_3 \times J_4}$, $1 \le j \le 5$ is the sub-tensor divided from the tensor $\mathcal{A}_0$ along the first order. Also, the corresponding high-order tensor equation will obtained according to Eq. 2, which will be processed in the cloud plane. Then the matching ratios will be computed by the edge plane, as shown in Fig. 5.

Finally, the matching results of the three mentioned scenarios are shown in Figs. 5a, 5b, and 5c, respectively. Taking Fig. 5a as an example, the first order is the hybrid order of I_2J_2, which has seven groups corresponding to seven expressions. Each group has six results corresponding to six degrees. The second order means five users, and the third order means the matching ratio. Taking the matching result of the first set scenario as an example, we find that the maximal matching ratio corresponds to (i_1 = 3 (the third user), i_2 = 3 (the third situation, "sadness"), j_2 = 4 (the fourth situation of degree)), which means that the third user is very tired and wants to sleep. Then the proactive and personalized services such as a shower with appropriate temperature will be automatically opened and the window curtain will be automatically closed. Also, the matching results of the second and third scenarios are (i_1 = 4, i_2 = 1, j_2 = 3) and (i_1 = 4, i_2 = 7, j_2 = 6), respectively. Then the fourth user will be told which restaurant that has her favorite food and is convenient with fewer customers in the second scenario. In the third scenario, the fourth user will be informed where the nearest shared bicycle stand is or even inform a nearby taxi to pick him up.

Conclusion

In this article, a cloud-edge computing framework including the cloud plane and edge plane is discussed. This framework, based on a tensor-based services model, is used to provide high-quality proactive and personalized services for humans. In addition, we introduce a tensor-based services model based on ServiceTensor for different scenarios. Also, for even more efficient service provision, several improvements such as optimized methods on computation between cloud plane and edge plane, and improved matching methods will be studied in future.

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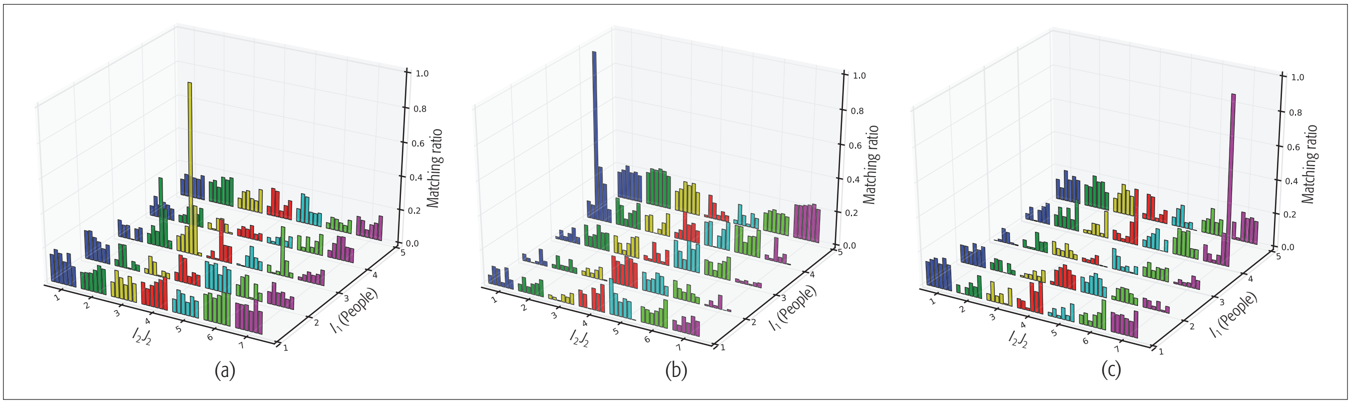

Figure 5. Matching results.

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Cyber-Physical-Social Systems (CPSS) represent an emerging paradigm encompassing the cyber world, physical world and social world. One of the main purposes of CPSS is to provide high quality, proactive and personalized services for humans. For CPSS to realize this purpose, a novel services framework is needed.