"Combat Cloud-Fog" Network Architecture for Internet of Battlefield Things and Load Balancing Technology

Yiming Wang, Zhiyuan Ren, Hailin Zhang, Xiangwang Hou, Yao Xiao

College of Communication Engineering, Xidian University, Xi'an 710071, China

The State Key Laboratory of ISN in School of Telecommunications Engineering

E-mail:{ymwang@s-an.org, zyren@xidian.edu.cn , hlzhang@xidian.edu.cn, xwhou@s-an.org, yxiao@s-an.org }

***Abstract*—Recently, the armed forces want to bring the Internet of Things technology to improve the effectiveness of military operations in battlefield. So the Internet of Battlefield Things (IoBT) has entered our view. And due to the high processing latency and low reliability of the "combat cloud" network for IoBT in the battlefield environment, in this paper , a novel "combat cloud-fog" network architecture for IoBT is proposed. The novel architecture adds a fog computing layer which consists of edge network equipment close to the users in the "combat-cloud" network to reduce latency and enhance reliability. Meanwhile, since the computing capability of the fog equipment are weak, it is necessary to implement distributed computing in the "combat cloud-fog" architecture. Therefore, the distributed computing load balancing problem of the fog computing layer is researched. Moreover, a distributed generalized diffusion strategy is proposed to decrease latency and enhance the stability and survivability of the "combat cloud-fog" network system. The simulation result indicates that the load balancing strategy based on generalized diffusion algorithm could decrease the task response latency and support the efficient processing of battlefield information effectively, which is suitable for the "combat cloud- fog" network architecture.**

Keywords—the Internet of Battlefield Things; combat cloud-fog; fog computing; load balancing

I. Introduction

The Internet of things (IoT) is an emerging paradigm that allows the interconnection of devices which are equipped with electronic sensors and actuators [1]. Recently, there is an interest in the defence community to leverage the benefits enabled by the IoT to improve the combat efficiency in battlefields and effectively manage war resources. This emerging area of using IoT technology for defence applications is being referred to as the Internet of Battlefield Things (IoBT) [2].

In the Internet of Battlefield Things, the deployment of a large number of sensors, the application of the Internet of things and intelligence system will generate massive intelligence data [3]. Besides, the accuracy of attack and decision-making are directly affected by the real-time, validity, and accuracy of intelligence data processing. The existing battlefield information system architecture has been unable to meet the demand of efficient information processing in the battlefield environment, while the powerful computing capability of cloud computing can better meet this demand [3]. In 2013, the concept of "combat cloud" was proposed by American general Michael Hoss Diki, and he tried to introduce "cloud computing" technology into the field of collaborative warfare. In 2014, American aviation weekly published the concept map of "combat cloud", describing the prospect of "air superiority air space cloud of the combat side". And China has also begun to study the "combat cloud" to cope with a new form of warfare in the network area in recent years.

However, since the cloud processing center is far away from the combat units, a large amount of battlefield data is transmitted to the cloud, and the related decision information will be returned to the combat units after cloud processing. It will lead to larger communication overhead and time delay, and thus can not effectively deal with the battlefield delay-sensitive tasks (such as high-speed target interception, UAV formation rapid response, etc.). At the same time, with the increasing of battlefield data, the burden of cloud processing center and communication bandwidth is getting heavier, leading to the low reliability of "combat cloud" architecture, which can not meet the requirement of high reliability of combat missions. In addition, the cloud processing center is bound to become the focus of attack targets due to its large amount of data and computing capability, and the survival problem in the battlefield environment will become extremely prominent.

The "combat cloud-fog" has entered the views of people in order to solve the above challenges in the "combat cloud" based IoBT architecture. The concept of fog computing was first proposed by Cisco in 2012 [4], and its core idea is to provide computing, storage, and network services for end users with network edge devices. In the "combat cloud- fog" network, the computing capability of fog equipment architecture is weak, and it is difficult for a single equipment to effectively deal with large amounts of data. Therefore, how to make use of massive network equipment for distributed computing and to balance the loading between fog equipment to reduce the computing latency has become an urgent problem in the "combat cloud-fog" network architecture.

Load Balancing is the core technology in distributed computing, with the goal of allocating reasonable

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resources for tasks, so as to maximize the benefits sought [5]. In [6], [7], [8], there are a lot of works have studied the load balancing strategy of cloud computing environment. However, although the fog is considered as a cloud close to the end users, due to the heterogeneity of fog equipment, cloud computing load balancing strategy can not be directly applied to fog computing. At present, only a few literatures have studies the load balancing strategy of fog computing, the literature [9] put forward that distributed computing between fog nodes can be used to improve the computing speed, but did not propose a specific distributed load balancing strategy. In the literature [10], a multi-band load equalization access strategy in fog computing is proposed to control the access of mobile equipment to the more idle frequencies and to balance the number of users on two frequencies, but the load balancing strategy for task processing is not considered. Therefore, in this paper, it will be proposed to study the load balancing strategy of the fog computing layer in “combat cloud-fog” based IoBT architecture to reduce the service response latency and to improve the combat capability.

II. The Basic Connotation and Characteristics of “Combat Cloud-Fog” Based IoBT Network System

A. Basic Connotation

“Combat Cloud-Fog”, a novel network architecture, which refers to add a fog computing layer to the architecture of a “combat cloud” based IoBT. The fog computing layer is a platform that can compute and store on the edge of the network, which integrates the dispersed combat fog equipment by using network communication technology, virtualization technology, distributed computing technology and load balancing technology. As a whole, “combat cloud-fog” based IoBT can be regarded as a resource pool to reorganize the available resources(such as network equipment, combat resources, etc.) on the battlefield.

B. Characteristics

“Combat Cloud-Fog” based IoBT not only retains the advantages of the original architecture of “combat cloud” based IoBT, but also possesses the distinct characteristics of the fog computing. Its specific characteristics are as follows.

1) Scattered Form and Aggregated Substance.

“Combat Cloud-Fog” based IoBT organically integrates the distributed combat resources by using the network communication technology and virtualization technology. Based on distributed computing and load balancing technology, the correlation analysis and trend prediction of the massive battlefield data obtained by each battle platform are carried out, and pushes the battle plan and situation data as required to achieve data sharing among platforms. The fog computing layer integrates the computing and storage ability of the combat network equipment near the client side, and provides data processing and storage service for the combat units at the edge of the network, effectively reduces the delay and the communication overhead.

2) Low Latency and High Reliability.

Combat fog equipment is close to combat units in the “combat cloud-fog” based IoBT architecture. According to the characteristics of surrounding users' information demands, relevant data and combat solutions can be actively downloaded from the cloud, and users can access the combat fog equipment to quickly obtain the required information. At the same time, the combat fog equipment receive the intelligence data transmitted by the combat units, process the data and provide localized computing to reduce data processing delay. Due to the large amount of collected data in the battlefield, the distributed computing can reduce the time delay between combat fog equipment, the result of computing and processing can be obtained in a short time and feedback to the combat units for decision-making, so as to support the purpose of delay sensitive application. In addition, the storage and processing of the data by fog computing can reduce the burden of the cloud and enhance network reliability. The storage and processing of data are distributed because that combat fog equipment are often scattered in the battlefield environment. Therefore, a certain or some combat fog devices will not be seriously damaged if they are attacked, and the network overall survivability is relatively higher.

3) High Elasticity and High Extensible.

In the "combat cloud-fog" based IoBT network, the cloud and fog computing layer can adjust their computing load according to the combat process, current situation and changes of user requirements, and adjust the proportion of tasks processed in the cloud and fog computing layer in real time, and have better flexibility, adaptability and plasticity in intelligence processing and scheme generation. On the other hand, the fog computing layer can be extended by wired/wireless connection, adding more combat network equipment to the original combat fog equipment cluster to meet the increasing demands of users. Meanwhile, the damage of partial combat fog equipment does not result in loss of computing power, and it can be reconstructed by quickly replacing damaged parts. High elasticity and extensible can guarantee the "combat cloud" based IoBT network system to meet the needs of combat dynamically, rapidly and maximally.

III. “Combat Cloud-Fog” Based IoBT Architecture

The “combat cloud-fog” based IoBT architecture, as shown in Fig.1, is divided into three tiers: the combat resource layer, the fog computing layer, and the cloud computing layer.

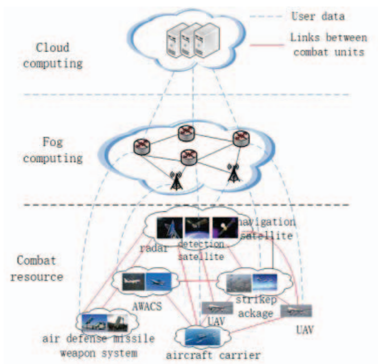

Fig.1 “Combat cloud-fog” Based IoBT architecture

The combat resource layer includes monitoring units, decision units, sensing units and weapon systems in the sea, land, air and space. Each unit uses its own sensor to search, detect and track enemy targets, collect comprehensive information, perform calculations based on task types in the fog layer or the cloud, and can achieve data fusion and sharing between different platforms so as to expand Information coverage, access to a comprehensive battlefield situation information.

The fog computing layer is composed of edge network equipment that has certain computing and storage ability in battlefield environment, which provides access to the combat units, local distributed data storage, and local distributed computing. The battlefield communication access network composed of edge combat network equipment which provides the access function of the random network, in the course of combat, it realizes the access ability of the combat units to access the battlefield communication network quickly. At the same time, due to the small storage capacity of a single combat fog equipment, the distributed redundant data storage method is adopted in the fog computing layer to manage the data information from local combat units to ensure the multiple backup and security of data. And the combat fog equipment can transmit the data stored on it to the cloud server, and actively buffer the relevant data from the cloud according to the local demand characteristics to share data. On the other hand, combat fog equipment receives data from the surrounding combat units, provides localized data processing services for combat units, and returns the relevant decision information based on its cached combat plans to the combat units. Compared with the original centralized data processing method in the cloud, the data transmission distance can be greatly shortened by the fog computing, thereby reducing the delay and better supporting the delay-sensitive service. Besides, the combat fog equipment can "clean", "filter" and "converge" the collected data, and transmit a small amount of data after processing to the cloud server to reduce the data transmission volume, so as to reduce the transmission delay.

Each combat unit stores the battlefield data collected on the cloud server, and obtains the useful information result through analyzing and mining the data, and updating the judgment of battlefield situation. At the same time, the cloud server optimizes and reorganizes the stored scheme in the combat plan repository according to the acquired battlefield general layout so that it can obtain the better combat plan, and shares the plan with the fog computing layer and each battle platform in real time. In addition, when the fog computation layer is overloaded, the cloud server can be used to deal with the application of low delay requirements.

IV. DYNAMIC LOAD BALANCING ALGORITHM OF "COMBAT CLOUD-FOG" BASED IOBT NETWORK BASED ON GENERALIZED DIFFUSION ALGORITHM

A. Load Balancing Theoretical Model of "Combat Cloud-Fog" Based IoBT Network

As can be seen from section 3, the combat fog network consists of scattered combat network devices with weak computing power. Although a single combat fog node can undertake the computing task, its weak computing power will greatly increase the task response delay. Therefore, it is of great significance to study distributed computing of multiple combat fog devices in order to effectively support time-delay sensitive tasks such as rapid target strike when processing a large number of battlefield data. Load balancing technology is the core technology of distributed computing, which can dynamically distribute and balance the computing load of the combat fog equipment according to combat fog equipment performance, communication cost and other parameters, and finally reduce the task response time delay. In response to the above problems, this paper studies the load balancing problem of "combat cloud-fog" based IoBT network.

Take the interception task in the battlefield environment for example. First, the local radar and other monitoring units search and discover enemy missiles in time and implement the detection and tracking of enemy targets. Then, we need to calculate the trace data and predict the trajectory. Due to the high speed of the missiles, if the tracking data is sent to the combat cloud for calculation, it is often unable to issue intercepting instructions as soon as possible. So information such as the trajectory, model, moving speed and altitude detected and traced can be transmitted to the local combat fog equipment to carry out distributed computing and to timely predict the movement trajectory of missiles and other information. Finally, under the command of the calculated information, the interception decision is generated and the decision is sent to the combat unit for interception. With refering to the above tasks, considering the "combat cloud-fog" based IoBT network architecture is composed of combat fog equipment that the number is k, whose network topology is shown in Fig.2 (where the fog computing layer network topology can be any topology). Combat units communicate with combat fog equipment, and combat fog equipment communicate with each other through wireless links, combat fog equipment and cloud servers communicate through wired links.

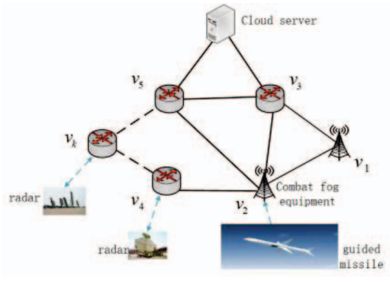

Fig.2 the network topology

The fog computing layer in the network topology shown in Fig.2 is abstracted into the weighted undirected graph G = (V, E) containing k fog nodes as shown in Fig.3. In Fig.3, the vertex set $\boldsymbol{V}=\{v_1,v_2,\cdots,v_k\}$, where vertex v_i represents the fog computing equipment. The edge set $\boldsymbol{E}=\{e_{v_1,v_2},\cdots,e_{v_i,v_j},\cdots e_{v_{k-1},v_k}\}$, where the edge $e_{vi,vj}$ represents the dependency of data processed between v_i and v_j, $w_{vi,vj}$ represents the weight value on the edge $e_{vi,vj}$.

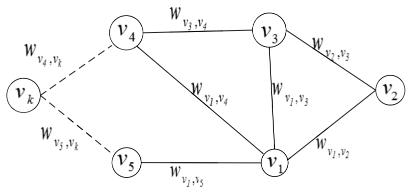

Fig.3 Abstract graph of the fog computing layer

In Fig.3, the computing capacity of each computing node v_i is set as C_{vi}, the communication delay between the combat fog equipment $\{v_i, v_j\}$ is indicated as $\tau_{vi,vj}$, $\boldsymbol{l}=\{l_1,l_2,\cdots,l_k\}$ is the current load vector on the combat fog equipment. In the process of dealing with a task, the combat units firstly submit computing tasks to combat fog equipment v_i which connect with combat units. And then balance the load of each combat fog device through the load balancing algorithm. When reaching the load balancing state, the load on the combat fog equipment v_i is set as $\overline{l_i}$, and the total time t that the total computing task processed in the fog network can be represented by the following formula.

$$t=\max\left\{\frac{\overline{l_i}}{C_{v_i}}+\tau_{v_i,v_j}m_{v_i,v_j}\right\} \tag{1}$$

In the formula, $\overline{l_i}/C_{v_i}$ represents the time required for v_i to process the current load $\overline{l_i}$ on it, $\tau_{vi,vj}m_{vi,vj}$ represents the communication delay between the combat fog equipment $\{v_i, v_j\}$. Among them, $m_{vi,vj}$ indicates whether there is a load transfer relationship between $\{v_i, v_j\}$, $m_{vi,vj}=1$ represents there is a load transfer relationship, $m_{vi,vj}=0$ means that there is no load transfer relationship.

B. Load Balancing Algorithm Based on Generalized Diffusion Model

The load balancing strategy is divided into centralized and distributed strategies based on the different control methods [11]. The centralized strategy manages the load of each compute node in the distributed system through the central control node and carries out task assignment and dispatch, which leads to the bottleneck of the central node performance, resulting in the low reliability and the damage resistance of the system and is not suitable for the combat environment. Distributed strategy has no central control node, and each node can transfer load to adjacent low load nodes. This method has good scalability, high reliability and survivability. Therefore, this paper intends to adopt a distributed load balancing algorithm based on generalized diffusion model [12] to design a load balancing strategy for the fog computing layer. Since there are a large number of application task requests in the battle environment, and a large number of applications require less delay. This paper uses the designed load balancing method to balance the task sent by the combat units to further reduce the service processing delay and support the application in the combat environment, so the load balancing strategy is applicable to all applications.

In the load balancing strategy, the combat units firstly send application tasks and data to fog equipment vi ,which connect with combat units. And then each fog equipment exchanges the load with the adjacent fog equipment, transferring part of the load to the adjacent fog equipment with lower load.At the same time, the load is received from other adjacent fog equipment with higher load, and the load balance state is achieved by exchanging a certain amount of load. When the load is exchanged between each of nodes and the neighboring node, the data required to process this part of the load is transferred to the neighboring node. Finally, each of the fog nodes processes the sub-computing tasks in parallel to complete the combat application tasks. The basic steps of the algorithm are shown in Alg.1.

Alg.1 Generalized diffusion dynamic load balancing algorithm flow

```
n=0;
while(convergence conditions are not satisfied) do
 for vi do
  for vj (all adjacent of vi )do
   vi send current load information li(n) to vj
   vi receive load information lj(n) from node vj
   transferred load Pij(n) = mji li(n) - mij lj(n)
   the transferred load of node vi:
        li(n+1) = li(n) - ΣPij(n)
   n=n+1
  end for
 end for
end while
```

Where, $\boldsymbol{l^{(0)}}$ is the initial load vector, $\boldsymbol{l^{(n)}}$ represents the load vector after n iterations, and $m_{i,j}$ represents the diffusion parameter. After iteration, the load vector can be expressed as $\boldsymbol{l^{(n+1)}}=\boldsymbol{Ml^{(n)}}$, $\boldsymbol{M}$ is a non-negative matrix and satisfies the following conditions[12].

$$m_{i,j}>0 \qquad if\{v_i,v_j\}\in \boldsymbol{E}或i=j \tag{2}$$

$$\sum_{v_i\in V} m_{ij}=1 \qquad v_j\in \boldsymbol{V} \tag{3}$$

$$m_{ij}c_j=m_{ji}c_i \quad v_i,v_j\in \boldsymbol{V} \tag{4}$$

The matrix $\boldsymbol{M}$ satisfying the above conditions is called generalized diffusion matrix. The formula (2) means that in each iteration, only the adjacent nodes can communicate with each other. The formula (3) keeps the load in a state that has no external condition interference. The formula (4) ensures that when the system load reaches equilibrium state, there is no load transfer between adjacent nodes.

In the generalized diffusion load balancing algorithm, one of the most important steps is the construction of the generalized diffusion matrix. The construction steps are as follows.

1）Define $\boldsymbol{A}$ as the association matrix of vertices and edges of weighted undirected graph G, $\boldsymbol{A}\in\{0,1\}^{k\times k}$. The line i of matrix $\boldsymbol{A}$ represents the relationship between vertex v_i and each of edges, and each column represents an edge of the graph.

2）Assuming that $\boldsymbol{B}\in\{0,1\}^{n\times n}$ is a adjacency matrix of G. The matrix $\boldsymbol{B}$ is symmetric since tha G is undirected. The elements in the i column/row of matrix $\boldsymbol{B}$ are 1 in all the neighbors of v_i.

3）The generalized diffusion matrices used in this paper are shown in the formula (5)

$$M = I - AS(\varepsilon)WA^T D^{-1} \qquad (5)$$

In the formula(5), D=diag(C_{v1},…,C_{vk}), W=diag($w_{v1,v2}$,…, w_{vk}), $S(\varepsilon)$ =diag($s_1(\varepsilon)$,…, $s_k(\varepsilon)$). Among them,

$$s_k(\varepsilon) = \min\left\{\frac{C_{v_i}}{\delta_i^w + \varepsilon}, \frac{C_{v_j}}{\delta_j^w + \varepsilon}\right\} \qquad (6)$$

δ_i^w is the weighting degree of the vertex v_i , and it has,

$$\delta_i^w = \sum\nolimits_{v_i \in e_{v_i,v_j}} w_{v_i,v_j} \qquad (7)$$

$$\varepsilon = 2e(G)\, w_{\min} \frac{C_{\min}}{C_{\max}} \sin^2\left(\frac{\pi}{2k}\right) \qquad (8)$$

w_{min} represents the minimum value of the weight $w_{vi,vj}$, C_{min} is the minimum value in the node computing capability of C_{vi}, C_{max} is the maximum value in the node computing capability of C_{vi} , $e(G)$ is the connectivity of edges in the figure.

V. Simulation and Analysis

In section 4, we make a theoretical model of the load balancing of cloud-fog network, and describe the principle and implementation steps of the generalized diffusion load balancing algorithm. This section compares the delay performance of the "combat cloud-fog" based IoBT network based on the generalized diffusion algorithm with the "combat cloud" based IoBT, and compares it with the weighted round robin (WRR)[13], random dynamic algorithm (Pick-KX) [14] and greedy load balancing algorithm (GreedyLB)[15] and other classic distributed strategy load balancing algorithm.

MATLAB is adopted in the simulation platform. The network topology of the fog computing layer is represented by its adjacency matrix, assuming that the number of combat fog equipment is 10. Referring to [16], set the computing ability of the cloud-fog network equipment. Meanwhile, in order to simulate the heterogeneity of the edge computing equipment in the real environment, the computing ability of the combat fog equipment is set not identical, as shown in Tab.1. In the real network environment, the communication delay $\tau_{vi,vj}$ between combat fog equipment mainly includes up-transmission delay, down-transmission delay and other delay. The upstream and the downstream transmission delay are related to the upstream and downstream bandwidth of the cloud-fog network. Other delays include queuing delay and propagation delay. Referring to [17], relevant communication parameters are set, as shown in Tab.1.

Tab.1 Parameters of cloud-fog network

Parameter type	*Cloud*	v_1	v_2	v_3	v_4	v_5	v_7	v_8	v_8	v_9	v_{10}
Cloud/Fog C_{vi} (MIPS)	1000	100	93	90	95	98	94	102	89	105	96
Up-bandwidth (Mbps)	2	84	86	71	80	83	86	89	89	87	79
Down-bandwidth (Mbps)	1.8	99	100	98	101	96	99	105	105	102	97
Other delay (ms)	10	1.5	1.4	1.2	1.1	1.2	1.3	1	1	1.3	1

Take the interception mission in the battlefield environment as an example, in [18], the first step is to send data from the radar to the data processing center, such as the moving speed of the interception target and the altitude from the ground. Then, the data processing center analyzes and calculates the intercept trajectory shape and situation, the location and time of the hit point according to the preset missile interception algorithm, and returns the result to the command center. In the simulation, consult the trajectory interception algorithm of reference [18], the amount of data required to carry out a missile interception mission request is about 1MB, and the number of instructions to be processed for a missile interception task is estimated to be 5 millions. In response to the above tasks, the number of task requests in the simulation, which varies from 0 to 300, and the data obtained from simulation are the average of multiple data.

A. Comparison of delay performance

We perform simulation experiments according to the network model in section 3. In the simulation, we compare the delay performance of "combat cloud-fog" network architecture in IoBT based on generalized diffusion load equalization algorithm and "combat cloud" architecture in IoT to validate the low latency performance of "combat cloud-fog" based IoBT. And the simulation result is shown as in Fig. 4.

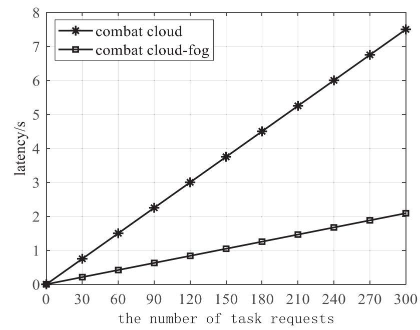

Fig.4 The comparison of task response delay

As you can see from Fig.4, when the number of task requests is lower than 30, the "combat cloud" architecture and the "combat cloud-fog" architecture in IoBT have a little difference in delay performance. Since that less data is transmitted when the number of task requests is relatively small, and the transmission delay caused by this task is small. Therefore, the computing capability of the cloud center can compensate for the delay loss caused by transmission. However, with the increasing number of task requests, because the cloud processing center is far away from the battlefield environment and the communication link bandwidth is small, the large data transmission will bring a large transmission delay, so the service response delay of “combat cloud” based IoBT is increased obviously. Compared with the "combat cloud" based IoBT architecture, the "combat cloud-fog" based IoBT network architecture has better delay performance because the fog computing layer is closer to the combat units and provides service for the combat unit at the edge of the network. When the number of task requests is 300, we can observe that the total task response delay of the "combat cloud-fog" based IoBT network architecture decreased by 86.64% compared with that of the "combat cloud" based IoBT. Therefore, the "combat cloud-fog" based IoBT network architecture can effectively reduce the task response delay and improve the service quality in the battlefield environment.

B. Comparison of delay performance of load balancing algorithm in battlefield environment

In the simulation ,we compare the generalized diffusion algorithm based on load balancing algorithm (GDA) with three distributed load balancing strategies: weighted round robin (WRR), stochastic dynamic -KX) and greedy load balancing algorithm (GreedyLB),results are shown in Fig.5.

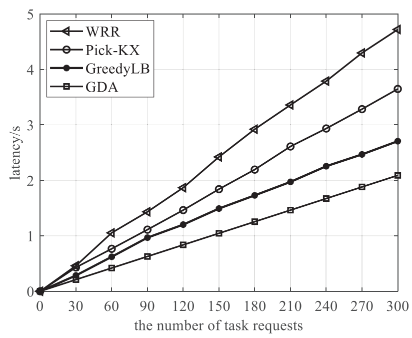

Fig.5 The delay performance comparison between generalized diffusion load balancing algorithm and classic load balancing algorithms

Fig.5 shows that when the number of task requests is less than 30, the difference between the task response delays of the four algorithms is not obvious. However, with the increasing number of task requests, none of the three algorithms can effectively reduce the delay because WRR, Pick-KX, and GreedyLB algorithms do not consider the communication overhead when the load is balanced. And the GDA algorithm takes into account the computing capability and communication overhead of the processor, so the advantages are more and more obvious. When the number of task requests is more than 90, the delay of GDA algorithm is obviously better than that of WRR, Pick-KX and GreedyLB algorithm, and the task response delay performance increases with the number of task requests. When the number of task requests is 300,the delay of GDA decreased by 55.72%, 42.71% and 22.78% compared with WRR, Pick-KX and GreedyLB algorithms respectively. The simulation result indicates that the "combat cloud-fog" based IoBT architecture based on generalized diffusion algorithm can effectively reduce time delay, which is suitable for battlefield environment..

SUMMARY

In this paper, we put forward "combat cloud-fog" based IoBT network architecture that adds a fog computing layer to "combat cloud", and describes the basic connotation and characteristics of "combat cloud-fog" based IoBT. This paper studies the load balancing strategy, and the simulation result indicates that the load balancing strategy based on generalized diffusion algorithm can effectively reduce time delay and improve service quality, which is suitable for "combat cloud-fog" based IoBT network architecture.

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