International Journal of Wireless Networks and Broadband Technologies
Volume 10 • Issue 1 • January-June 2021

Strategy for Reducing Delays and Energy Consumption in Cloudlet-Based Mobile Cloud Computing:

Problems on Mobile Devices, Problem Solution, Selection of Cloudlets According to User Requirements

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ABSTRACT

In the paper, the problem of using cloudlet-based mobile cloud computing to solve the issues (resource deficiency and limited energy) that require large computing and memory resources on mobile devices has been studied. Energy-saving of mobile devices, resource limitations in mobile devices, and elimination of network delays are analyzed. It is shown that the solution of mobile users' tasks in the cloud leads to the increased battery life of mobile devices and reduces network delays, which is shown by mathematical calculations. The article considers the balanced distribution of the tasks in the cloudlet network. The paper also deals with the selection of cloudlets according to user requirements. The cases for which a cloud application can be loaded by the user were evaluated and a model was proposed using the possible values that determine the importance of cloudlets (user proximity, high reliability, etc.).

KEYWORDS

Cloudlet, Connection Channel, Energy Consumption, Mobile Cloud Computing, Mobile Devices

INTRODUCTION

Reducing of computing and memory resources of mobile devices, and the short period of autonomous operation of a battery life creates problems which require large computing and memory resources. Mobile cloud computing has been used to overcome these problems (Pang et al., 2015; Dinh et al., 2013; Fernando et al., 2013). Cloud technology eliminates resource restrictions offering virtual resources such as SaaS (Software as a Service), PaaS (Platform as a Service), and IaaS (Infrastructure as a Server) for mobile devices. User's tasks are performed on cloud servers and the results are sent to the mobile device. When using this technology, the mobile device acts as a terminal, which allows saving energy. Thus, mobile cloud computing is a new paradigm created by the integration of mobile network and cloud computing, which

DOI: 10.4018/IJWNBT.2021010102

provides overcoming the computing and memory resources limitations on mobile devices and reducing energy consumption (Abolfazli, 2014; Sarddar, & Bose, 2014).

Moreover, solution of mobile users' tasks on remote cloud servers creates great problems. Mobile users are loaded on remote cloud servers via the Internet, and it may cause the occurrence of delays due to the overload of network and increase the energy consumption of the mobile device. The quality of the service (QoS) is low if the network is loaded. Mobile devices have become the main computing platform for many users. Recent software applications require great computing and memory sources. Limited computing and memory resources of mobile devices, low battery life cannot provide rapid solutions for these problems. Thus, the energy consumption of mobile devices, reducing resource limitations on mobile devices and network changes are of the main problems. When using a cloudlet-based network, numerous cloudlets appear around the user. More loading of one cloudlet and less loading of others will cause delays in the system. Balanced placement of the user's tasks on these cloudlets is the main problem. If a user loads and solves a task in a nearby cloud, there will be less delays and less energy consumption. The delays and energy consumption will increase with the growing number of communication channels if cloudlets are far away from mobile devices. Therefore, solution for selecting a cloudlet that satisfies the user's requirements in the cloudlet network is studied.

The article analyzes the issues of energy saving and resource limitations in mobile devices and the elimination of network delays. The introduction emphasizes that saving energy consumption of mobile devices, eliminating resource constraints and network delays in mobile devices are of great importance. Section 2 provides an overview of the studies in this field. Section 3 examines the factors that affect the time of task processing in mobile cloud computing and its delivery to the user, and suggests the use of hierarchically structured cloudlet-based mobile cloud computing to solve abovementioned problems. Section 4 compares energy saving when solving the tasks in cloudlets through the mathematical way and the delays that occur in cloudlets or cloud servers, and shows the advantages of cloudlets. Section 5 discusses the selection of cloudlets according to the user's request.

RELATED WORK

In some studies, energy consumption can also be reduced by placing the main and extra parts of the software applications that users use on their mobile devices and cloud servers (Huerta-Canepa & Lee, (2017). The article (Jia et al., 2016) shows that the delays in data sharing are long-term as the cloud servers are physically far away from users. The proximity of cloud servers to the users significantly reduces the delays in data sharing (Shi et al., 2012). In the article (Alakbarov R, & Alakbarov O, 2019) a method is developed to ensure the efficient use of cloud sources by mobile users. In the paper, the issue of how to properly use cloudlets located on the mobile user's route in wireless metropolitan area networks (WMAN) is described. Some investigations (Li & Wang, 2013) propose the use of cloudlets to reduce computing load on mobile devices. In (Gelenbe, Lent & Douratsos, 2012) the problem of reducing energy consumption by the optimal distribution of a user-solved problem between a cloud server and a remote cloud server is described. In (Mukherjee et al., 2014; Ahmed et al., 2015; Beloglazov et al., 2012) the issues of software application delays and the development of mobile computing systems that reduce energy consumption are discussed. The paper (Garrison, Wakefield, & Kim, 2015) considers saving energy consumption on mobile devices using cloudlets. The usage of cloudlets to avoid delays on the Internet while solving mobile users' problems in remote clouds is studied (Satyanarayanan et al., 2009). The paper (Tawalbeh, Jararweh & Dosari 2015) studies the selection of cloudlets that serve more efficiently for mobile devices. It is shown that security issues when using the cloudlet network are higher than using the cloud servers (Quwaider & Jararweh, 2015). The article (Verbelen et al., 2014) shows the use of cloudlets as a way of solution in the reduction of delays and energy consumption. In (Bohez et al., 2015), a method for the efficient use of cloudlet sources by mobile users is proposed. The balanced distribution and management of issues in a cloudlet-based mobile computing network is investigated (Singh & Chana, 2015; Li, 2012;

Shiraz & Gani, 2014). The paper (Mathur & Sharma, 2019) various issues in mobile devices (related to energy shortages, computing resources, etc.) are analyzed and solutions are proposed. The article (Nayyer, Raza, & Hussain, 2018) proposes the use of cloudlet-based cloud computing to eliminate the delays caused by overload in mobile cloud computing and a method of efficient use of cloudlets. In (Somula, & Ra, 2018) suggested to use cloudlets to troubleshoot problems with mobile device batteries and computing resources, and to eliminate delays in resolving user software applications in cloudlets. The article (Zhao & Zhou, 2019) reviewed saving energy consumption in solution of the issue. It proposes can reduce energy consumption and communication channel delays by correctly placing main and auxiliary parts of software application used by the users in the mobile device and cloud server. In (Ceselli, Premoli, & Secci, 2017) discusses the structural problem of a cloudlet-based network. The article suggests how to create a cloudlet network in Wireless Metropolitan Area Networks in order to solve the problem of where and how many cloudlets are deployed.

PROBLEMS OF MOBILE DEVICES

The factors that affect the processing of tasks and the time of delivery of the results to the user in the mobile cloud computing are as follows: (Fernando et al., 2013; Sarddar & Bose, 2014; Shiraz & Gani, 2012).

- Timing of solving the task on remote cloud servers
- Network delays
- Data transferring speed in communication channel

The last two factors depend on the network environment. In mobile cloud computing, the occurrence of delays increases as the connection between the user and the remote cloud server is performed over the Internet. Today, the centralized clouds used by users cannot send processed data to users at high speed although they have high computing and memory resources. The rapid increase in the number of mobile users in cloud computing causes network overload, which can lead to delays in the transfer of processed data to the user. According to the Global No.1 Business Data Platform, the number of smartphone users is expected to reach 3.8 billion in 2021 and their monthly internet traffic is expected to reach 12 GB/month in 2022. Using these centralized mobile cloud computing within these figures, it is impossible to provide users with efficient cloud services. To overcome the mentioned shortcomings, it is necessary to locate the cloud computing resources close to the user. The tasks that require large resources from mobile cloud computing are loaded on nearby servers, helping them to resolve the tasks more quickly.

Mobile devices face the following difficulties in the solving of the tasks that require large amounts of computing and memory resources:

- Restrictions in the energy resource
- Restrictions on computing and memory resources

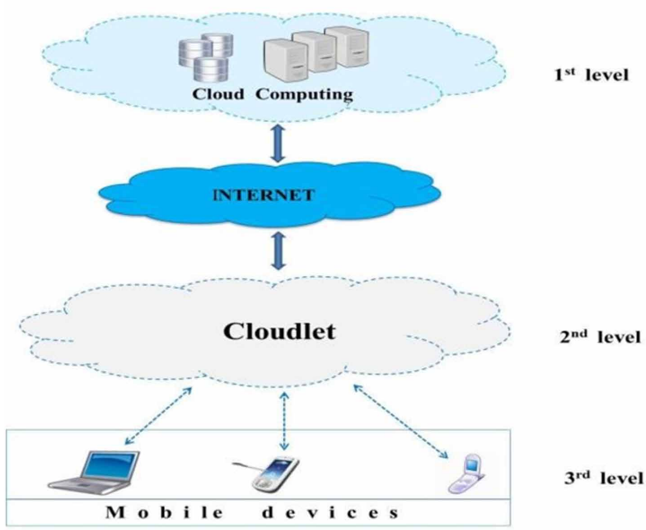
Battery life of mobile devices is limited. The implementation of applications on cloud servers reduces energy consumption on mobile devices. However, to completely offload all the application to the cloud is impossible. For example, features such as launching applications, data input and displaying processing results on screen, etc. should be implemented on a mobile device. The implementation of most applications can be run on cloud servers. Some part of the energy of mobile devices is spent on displaying various information on the screen, to solve a particular task and connect it to the Internet (Kumar & Lu, 2010). The use of social networks, Internet applications, phone calls, web pages, etc. often causes the frequent discharge of the batteries of the mobile device and requires to charge it all day. Existing technologies do not ensure a longer battery life of mobile devices. Cloud technology is used to extend battery life (energy saving). In the use of applications that require large computing and memory sources on mobile devices, their processor and memory sources are fully involved in outlined issues. This, in turn, causes a quick discharging of the battery. Cloud technology is used to solve this problem. That is, a task is solved on cloud servers and the mobile device acts as a terminal. As a result, this provides longer battery life. At the same time, when mobile devices connect to the network through Wi-Fi, energy consumption is reduced by 23% compared to other connection technologies. Also, the more the applications are resolved on servers close to mobile devices, the faster the task can be solved by reducing delays in the communication channel, and the energy consumption of the mobile device.

Thus, cloudlets are created near the base stations of mobile operators for larger and more efficient use of mobile devices in cloud technologies. Cloudlet (small cloud computing) are devices located nearby the users (server, desktop, notebook, etc.), which enable them to process and report the tasks faster compared to remote cloud servers. Cloud services required by the users are implemented through cloudlets. Let the user has to work with any software. He calls the software to the nearest cloudlet and works with it for the right period of time. This reduces the cost of cloud services, decreases the time required to solve the task, and the network is less loaded. On the other hand, utilizing traditional centralized cloud services can provide the requirement for mobile devices for high computing and memory sources. But there occur delays in obtaining results or data in this type of cloud service. For solving the presented problems, the usage of hierarchical structured, cloudlet-based mobile computing systems is proposed. The system sends those operations to cloudlets to perform the processing operations required by mobile devices and to achieve the final result. It also minimizes the transfer delays, reduces the limitations of computing and memory sources of mobile devices, and also reduces the energy consumption of mobile devices.

While using the cloud computing service, the user applies two modes: offline, online. For example, the user obtains a virtual computing machine from the cloud for issues that require high computing power. Then, he sends he tasks to the cloud and gets the results in a while. In this mode, there is no direct connection between the user's computer and the cloud within the time required to solve the task. However, there is a problem between the user and the cloud to the end of the process. It causes network loading when solving these tasks. A new architecture of mobile cloud computing is used to reduce network overload. Sometimes it is called centralized cloud technology. The studies show that the volume of mobile devices and the number of mobile internet users are constantly increasing. Mobile computing systems with a single level of architecture cannot provide high-quality service to many users. That is, in mobile network systems, the cases such as network overload, late transfer to the user, cost of service, delays, and traffic overload do not provide quality service. Resource management centre (RMC) widely uses hierarchical structured cloudlet-based mobile cloud computing to solve these shortcomings (Figure 1) (Sarddar & Bose, 2014; Alakbarov R & Alakbarov O, 2019).

Mobile user requests and data are transferred to RMC, which provides services for the cloudlet network. Then, users' requests are sent to the server providing Internet access at the RMC and through the Internet, the connection to the appropriate cloud is supported. The RMC contains information on the technical capabilities of computer hardware (processor running speed, number of processor cores, number of virtual machines and their specifications, memory, etc.) used to create cloudlets, which enable users to load and solve their issues on a nearby cloudlet. Thus, according to submitted request, the application called from the cloud servers is deployed on the cloudlet providing the user's requirements. This architecture partially improves the performance of some specified parameters (problem resolution time, delays in the communication channel, fractures, etc.). In the hierarchically structured architecture, cloud computing systems are located on the 1st level, and on the 2nd level, a network of cloudlets is created close to the base stations. On the 3rd level, mobile devices are located. The advantages of using cloudlets include fast service access, supporting of mobility and reducing

Figure 1. The architecture of the hierarchically structured cloud computing



roaming costs. Resolving user software applications in nearby cloudlets can save energy consumption on mobile devices and partially reduce network delays (Whaiduzzaman et al., 2016; Roy et al., 2017).

In addition, the technical capabilities of cloudlets are higher than those of mobile devices as in cloud computing, which enables the implementation of time-consuming software applications on cloudlets. Let's consider the energy-saving time of the time in the cloudlet and the delays that arise when using the cloud or cloud servers.

PROBLEM SOLUTION

$(P_{mob)})$ - is the energy consumption used in the solution of the problem in a mobile device:

$$P_{mob} = P_m \times T_m = P_m \times \frac{\boldsymbol{0}}{M} \tag{1}$$

where, P_m – is the energy consumption of the mobile device in solving the task (in a single time period), $\boldsymbol{0}$ – the number of instructions in the issue, M - computing performance of mobile device (the number of instructions performed in a single period), T_m – time for solving the task on mobile device.

Let's see the energy consumption of the mobile device when solving the task in the cloudlet:

$$P_c = P_1 + P_2 + P_3$$

where, P_1 denotes energy consumption of the mobile device in standby mode while solving the task in the cloudlet, P_2 and P_3 - the energy consumption of the mobile device when offloading the tasks from the mobile device to the cloudlet. Energy consumption is estimated by the following formula:

$$P_c = P_{m1} \times \frac{\boldsymbol{0}}{c} + P_{ts} \times \frac{D_{ts}}{d_s} + P_{tr} \times \frac{D_{tr}}{d_r} \qquad (2)$$

where, P_{m1} – energy consumption of the mobile device in a standby mode while solving the task in the cloudlet in a single time, C – computing performance of cloudlet, $\boldsymbol{0}$ – the number of instructions in the task, P_{ts} – energy consumption of mobile device in a single time when offloading the tasks to the cloudlet, D_{ts} – the volume of transmitted data, d_s – the speed of delivery channel, P_{tr} – the energy consumption of the mobile device in a single time when obtaining data from the cloudlet, D_{tr} – the volume of data received, d_r – the speed of the receiving channel.

For simplicity, if the energy consumption of mobile device in a single time is accepted as $(P_{ts} = P_{tr} = P_{sr})$, transferring and obtaining speeds as $d_s = d_r = d_{sr}$ then, the formula [2] will be as follows:

$$P_c = P_{m1} \times \frac{\boldsymbol{0}}{c} + P_{sr} \times \frac{D_{ts} + D_{tr}}{d_{sr}}$$

Task offloading from the mobile device to the cloudlet and receiving results doesn't take much time, and it provides to reduce the energy consumption of the mobile device for these tasks. Since the computing performance of the tools (C) used in the cloudlets is much more than the computing performance of the mobile device $(M)(C = KM, K - \text{acceleration coefficient})$, the task will be resolved faster in the cloudlet and the energy consumption of the mobile device will be less. Thus, saving energy consumption (P_q) will be as follows:

$$\begin{aligned}P_q &= P_{mob} - P_c = P_m \times \frac{\boldsymbol{0}}{M} - (P_{m1} \times \frac{\boldsymbol{0}}{c} + P_{sr} \times \frac{D_{ts} + D_{tr}}{d_{sr}}))\\ &= P_m \times \frac{\boldsymbol{0}}{M} - P_{m1} \times \frac{\boldsymbol{0}}{KM} - P_{sr} \times \frac{D_{ts} + D_{tr}}{d_{sr}} = \frac{\boldsymbol{0}}{M}(P_m - \frac{P_{m1}}{K})\\ &-P_{sr} \times \frac{D_{ts} + D_{tr}}{d_{sr}}\end{aligned} \qquad (3)$$

Thus, the energy consumption of the mobile device is not high when offloading the data to the cloudlet and obtaining results. As seen in the formula (3), the energy consumption of the mobile device in standby mode depends on how fast (K-acceleration coefficient) the task is solved in the cloudlet. The sooner the matter is resolved on the cloudlet, the more the mobile device will save energy. Thus, if the value of the formula [3] is a positive figure (P_q), then the mobile device will save energy consumption up to the same figure. For (P_q) being a positive figure, the transmission and reception speed d_{sr} should be higher and the cloud computing performance (C) should be higher to allow the mobile device to spend less energy in standby mode. If (P_{mob}) - the energy consumption on a mobile device for solving the task issue is less than (P_c) - the energy consumption when solving the task on the cloudlet, then the mobile device is used $(P_{mob} < P_c)$.

Let's study comparative analysis of the delays that arise when solving the tasks on cloudlet or cloud servers. If the issue is solved in the cloudlet, delays are evaluated as follows:

$$T_{cloudlet} = T_1 + T_2 + T_3 + T_4$$

where, $T_1 = \frac{\theta}{s}$ – is the task solution time in the cloudlet, $T_2 = \frac{D_{ts}}{d_s}$ – task offloading time from the mobile device to the cloudlet, D_{ts} - the volume of data transmitted from a mobile device to cloudlet, d_s - transmission channel speed. $T_3 = \frac{D_{tr}}{d_r}$ – transferring time of the result from the cloudlet to the mobile device, D_{tr} - the volume of the data received, d_r - receiving channel speed. $T_4 = \frac{D_{mc}}{d_{mc}}$ - network latency, D_{mc} - the distance between the mobile device and the cloudlet, d_{mc} - network broadcast speed. Thus, the delays when the task is solved in the cloudlet are calculated as follows:

$$T_{cloudlet} = \frac{\theta}{C} + \frac{D_{ts}}{d_s} + \frac{D_{tr}}{d_r} + \frac{D_{mc}}{d_{mc}} \qquad (4)$$

Let's analyze the delays that arise in resolving the tasks on cloud servers:

$$T_{cloud} = \frac{\theta}{C_{cloud}} + \frac{D_{ts}}{d_s} + \frac{D_{tr}}{d_r} + \frac{D_{mc}}{d_{mc}} + \frac{D_{mcloud}}{d_{mcloud}} \qquad (5)$$

where, $\frac{\theta}{C_{cloud}}$ - is the task solution time on the cloud server, C_{cloud} - performance of the cloud server where the task is solved, $\frac{D_{mcloud}}{d_{mcloud}}$ - network delays, D_{mcloud} - the distance between the mobile device and the cloudlet, d_{mcloud} - network broadcast speed.

Let's compare formulas (4) and (5). For simplicity, if the performances of virtual machines used by cloudlets and cloud servers are taken into account as the same, then the major delays in resolving and transferring the task to the mobile user will depend on the data transmission, reception of results, and the transferring capacity of the network. The above-mentioned parameters will increase when solving the task on cloud servers as the result of network overload and it will cause delays. Therefore, delays will be less if the tasks are resolved on the cloudlet. Thus, when the tasks are resolved in the cloudlet, there will be less energy consumption and delays.

Below the experimental results of using mobile cloud and cloudlet are compared to solve the mobile user's tasks. The mobile user uses 4G to connect to the cloud server, and the wireless connection (Wi-Fi) to connect the cloudlet.

The following equipment are used for the experimental tests:

- Cloudlet: Lenovo V110 laptop (Core i5- 6200, CPU- 2.4 Ghs, RAM - 8 GB, HDD - 256 GB)
- Mobile phone: Samsung Galaxy Note 8 Exynos Octa 8895 (CPU - 2.3 Ghz, RAM 6 GB, HDD - 64 GB)

To test the application of the proposed model, both the cloudlet and a remote cloud server of an enterprise are used. The size of the downloaded file is 120 Mb. During the experiment, the energy consumption of downloading the file to the mobile phone is compared with the time required to complete the operation and to finish the whole process. When downloading from a remote cloud server, energy consumption is 98.2 mW, and delays are accounted for 6.54 seconds. Experiments show how the cloudlets are more efficient for users rather than the remote cloud server. Thus, using a cloudlet, mobile devices consume 1, 2 times less energy than a remote cloud server and about 1.3 times less latency occurs. When using remote cloud servers, the transfer of large files is often time consuming, whereas the delays occurring when using cloudlets are shorter. Thus, it is proven that cloudlet-based mobile clouds are much more efficient for the fast processing of software applications running in the cloud or in the cloudlet and for the reduction of device's energy consumption and latency.

SELECTION OF CLOUDLETS ACCORDING TO USER REQUIREMENTS

Numerous cloudlets of the cloudlet-based Wireless Metropolitan Area Networks (WMAN) are used. Cloudlet-based network RMC contains information about the technical capacity of computer (server, desktop, notebook, etc.). Moreover, RMC collects information about the technical capacity of cloudlets (processor frequency, number of processor cores, number of virtual machines and their technical characteristics, storage capacity, etc.) and which base station the cloudlets are close to within the mobile network. Therefore, according to the received query, it is important to know in which cloudlet or virtual machine the user can place the application called from the cloud servers that meets the user's requirements. In many cases, users do not choose the type of virtual machine according to the resources required to solve the task. By providing the users with the solution of queries in nearby cloudlets, it is possible to eliminate the delays by reducing the number of communication channels between users and cloudlets and ensure reliable operation of the network. Proper deployment of software applications used by users in the cloud may reduce the energy consumption, latency and interruptions.

Given the size of WMANs, improper deployment of user tasks in cloudlets and improper distribution of load among them (some cloudlets are overloaded, others are partially used or not used at all) can lead to longer connection and increased processing time and delays in delivering the results to the user. On the other hand, taking into account the fact that cloudlets have different computing and memory resources, and it should be determined which of them is less loaded, and the user's application should be installed and run on it. Thus, the optimal deployment of software applications of multiple users in the cloud is a topical issue. To overcome this shortcoming, it is necessary to locate cloud computing resources close to the user. Users can eliminate these delays by using a cloudlet located closer to them. Cloudlets also process the requests faster and enable the mobile devices to consume less energy.

When computing and memory resources of a cloudlet fail to handle the requests of its multiple mobile users, the mobile user has to select another cloudlet that is close to him/her and use its resources. The time of task solution and delivery to the user depends on the computing power of the virtual machine created in the cloudlets and on the number of nodes between the cloudlet and the user. The smaller the number of nodes between the cloudlet and the user, the fewer the delays occcur. This, in turn, helps deliver the results and data to the user faster. Before choosing a cloud, the network needs to be inspected and the status determined. Thus, after the inspection, the information about the loading and technical capabilities of cloudlets is obtained, and when the request is received, it is determined in which cloudlet the task will be resolved faster. The number of communication channels between users and the cloudlet should be minimal, which ensures reliable operation of communication channels. At the same time, a small number of communication channels reduces the delays and increases the reliability of security issues.

Potential cloudlets should be evaluated by the user in the deployment of the software on any cloudlet. In the implementation of the evaluation, the characteristics of the cloudlet should be taken into account. Let's analyze the selection of cloudlet relevant to the users' requirements (vacant resources in the cloudlet, reliability of communication channels, minimum number of communication channels, distance from the user to the mobile base station).

The cloudlet-based mobile computing system consists of cloudlets in W number (Figure 2). Mobile user significantly reduces the delays by offloading their tasks to the nearest cloud that provides its solution. These cloudlets contain geographical coordinates, computing power, and reliability indicators for each particular cloudlet and information about the free virtual machine resources management centre (RMC) in the cloud. Cloudlet coordinates being:

$$C_1(x_1,y_1),C_2(x_2,y_2),...,C_w(x_w,y_w)$$

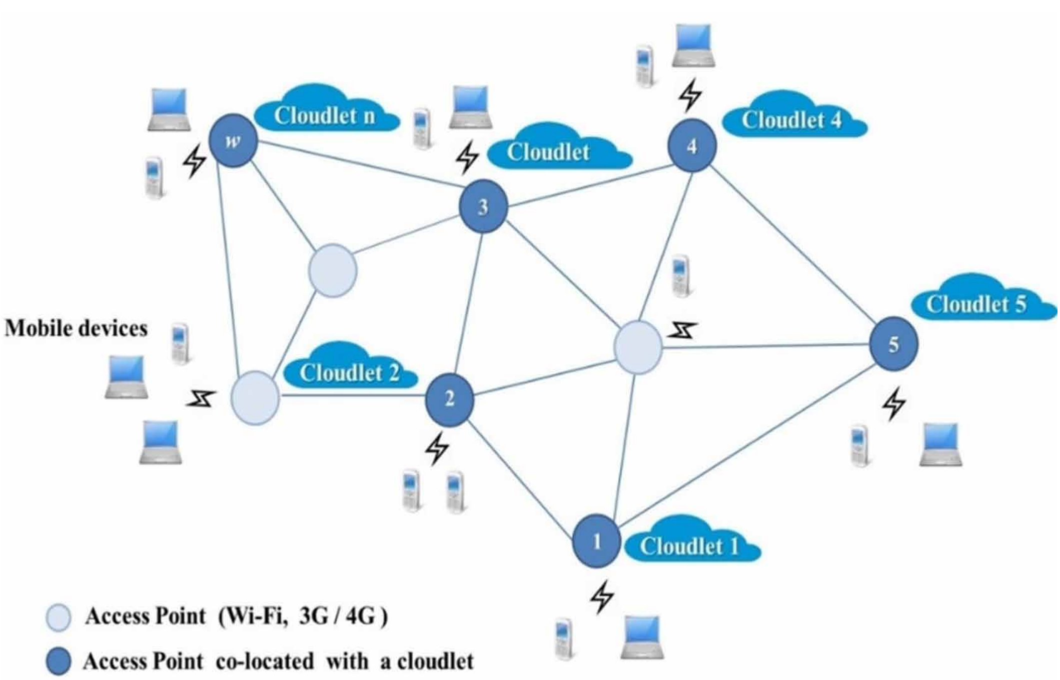
creates clusters:

$$C=\{C_w(x_w,y_w)\},w\in[1,W] \tag{6}$$

When using the cloudlets by users, the availability of vacant resources for the task solution should be provided. Cloudlets serve to the user according to the number of virtual machines created in there.

Overloading occurs on the network when the number of users exceeds the number of virtual machines. Therefore, users' tasks have to be distributed balanced between cloudlets. The computing power of cloudlets is determined by the computing power of the computer hardware used there. Since each user is associated with a virtual machine, the presence of a vacant virtual machine just means

Figure 2. Cloudlet-based mobile computing network



the presence of free computing power in the cloudlet. Cloudlets clusters (W) with vacant resources are determined from cloudlets clusters when the user addresses them - $C^N = \{c_n; n = 1,..., N\}, N$ – is the total number of cloudlets with vacant resources $N < W$. It is considered that the characteristics of the cloudlets are sufficient to solve the users' tasks. The reliability indicators of computer hardware used in the creation of cloudlets (desktop, netbook, notebook, server, etc.) vary. A cloudlet with a high-reliability index may be required, depending on the character of the user's task. Set of cloudlets are defined from the cloudlets with vacant resources according to reliability indices required by users. $C^M = \{C_m \in C^N \mid p_m > p_{\min}\}$ – is a set of cloudlets in which reliability indices satisfying the condition $p_m > p_{\min}$ are defined; $p_{\min}$ – is a predetermined low bounded value of reliability; $m = 1,..., M; M$ – is the number of cloudlets in clusters C^M , $M \leq N$.

Note that, depending on the solution of particular problems, other characteristics of cloudlets may also be involved in the analysis process. Furthermore, new characteristics can be identified and considered if necessary.

Let at any current moment, mobile stationary users J in a U_j number be connected to the network of cloudlets determined in formula (6) if $\forall j \in [1, J]$. These users, together with their coordinates, create a set of $\{U_j(x_j, y_j)\}$. As in a set of cloudlets, each user of the set of users has their requirements for computing resources and reliability indices of cloudlets. If the users' requirements j are determined as c_j, p_j then the set of users should be defined as follows:

$$U = \{U_j(x_j, y_j), \{c_j\}, \{p_{ji}\}, j \in [1, J]\}$$

Moreover, each user can connect to cloudlets if the condition $dis_{jk} \leq d_{\max}$ $(dis_{jk} - j$ – th mobile user's connection distance to the k – th cloudlet, $d_{\max}$ – maximal connection distance from the mobile device to base station is satisfied (signal reception diapason), and if the number of communication channels between the j –th mobile user and the k -th cloudlet is no more than $L_{jk} \leq L_{\max,}$, (for example, $L_{jk} = 2$). According to parameters, the set of users can be defined as follows:

$$U = \{U_i(x_i, y_i),\ \{c_j\}, \{p_j\}, \{d_j\}, j \in [1, J]\}$$

A cloudlet with a minimum number of communication channels should be selected in the connection between the user and the cloudlet to ensure the high reliability of communication channels. Thus, the selection of the cloudlet is implemented according to the users' requirements (existence of vacant resources in the cloudlet, high reliability indices of cloudlets $(p_k \geq p_{\min})$, minimum number of communication channels $(L_{jk} \leq L_{\max)}$, connection distance from the user to the cloudlet $dis_{jk} \leq d_{\max}$ and etc.):

$$C^K = \{C_k \in C^M \mid (L_{jk} < L_{\max} \ \&\ dist_{jk} \leq dist_{\max})\},$$
$$k = 1,..., K, K \leq M$$

where:

- L_{jk} : is the number of communication channels from the j-th mobile user to the k-th cloudlet;

- $L_{\max}$: is the maximum number of communication channels accessible from the mobile user to the cloudlet;
- $dist_{\max}$: is the maximum connection distance from the mobile users to the mobile base station (cloudlet);
- K –is the number of cloudlets in the set of C^K (selected within given conditions) $K \leq M$.

The distance between the J -th user $u_j(x_j, y_j)$ and the k -th cloudlet $C_k(x_k, y_k)$ is an Euclidean distance and $dist_{jk}$ is evaluated as follow:

$$dist_{jk} = \sqrt{(x_j - x_k)^2 + (y_j - y_k)^2} \leq dist_{\max}$$

Here, (x_j, y_j) and (x_k, y_k) – is the geographical coordinates of the j -th mobile user and the k-th cloudlet. For the connection of the j-th user to the k-th cloudlet, the cloudlets satisfying the following conditions are selected:

$$\begin{cases} dis_{jk} \leq d_{\max'} \\ l_{jk} \leq l_{\max'} \\ p_k \geq p_{\min} \end{cases} \tag{7}$$

The first line of (7) refers to the distance parameter between the user and the cloudlet, the second line refers to the number of communication channels of the user with the cloudlet, and the third line refers to the parameter of reliability.

Thus, using the possible values (c, d, l, p) that determine the importance of cloudlets, it can be defined to which cloudlet to offload the users' software on the cloud.

CONCLUSION

The article studied the factors (solution time on cloud servers, network delays, data transfer rate through communication channel) affecting the processing time of the tasks in mobile cloud computing and delivery of the result to the user. The network delays occurred during the solution of the user tasks on remote cloud server or cloudlets were comparatively analyzed. Solving tasks in cloudlets reduced the network delays and explained through mathematical calculations. Solving the user tasks in cloudlets also saved energy consumption of mobile devices and eliminated resource limitations of mobile devices. At the same time, the article discussed the issue of selecting cloudlets that meet some of the user requirements. Using the possible values (closeness of the user, high reliability, etc.) that determined the importance of cloudlets, the conditions according to which the user upload his application to cloudlet were identified. A strategy for selecting cloudlets according to user requirements was developed and a solution to the problem of balanced task distribution among cloudlets was offered.

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