A Cost-Aware Method for Tasks Allocation on the Internet of Things by Grouping the Submitted Tasks

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Abstract

Internet of Things (IoT) as a new paradigm is described the future in which physical objects such as RFID tags, mobile phones, sensors, actuators, etc. are related to the Internet and can interact with each other to reach the defined objectives. One of the important goals in this paradigm is performing the submitted tasks using the task allocation mechanism. Since there is a complex relationship among devices, the task allocation in the IoT is very sophisticated. To solve this problem, in this paper, we suggest a hybrid algorithm using a combination of the Heterogeneous Earliest Finish Time (HEFT) and the Triplet algorithm for task allocation in the distributed IoT to minimize the makespan and communication costs among objects. Also, a comparative study of the HEFT, Triplet, and the proposed algorithm have been done. Experimental results using Cooja simulator have shown that the proposed algorithm reduces communication costs.

Keywords: Internet of Things, Service, Task allocation, Makespan, IoT

1 Introduction

Recently, the Internet and Information Technology (IT) improved our life by offering new services [1-8]. Internet of Things (IoT) as a new IT and Internet-based technology was introduced by Ashton [9]. It has a collection of a number of physical devices which provides the communications ability among these devices and leading to anywhere and anytime communications of anything [10-14]. The IoT provides an extension of the current Internet to greatly expand the Internet to hold a wide range of physical objects and devices that exhibit pervasive sensing, computational, and actuation abilities [15-20]. In fact, the IoT is a network of connected geographically distributed objects using standard communication protocols [21-26]. The IoT concept defines the systems that rely on independent communication of a collection of physical objects [27]. These heterogeneous objects realize a highly dynamic and distributed networked system [28-29].

On the other hand, task allocation, placement, and scheduling are the most famous NP-hard problems [30-35]. The main purpose of placement and allocation mechanism is to allocate the tasks on proper resources in which they can be executed under problem-specific constraints [36-39]. Furthermore, IoT is characterized by the dynamic behavior of their nodes [40]. Therefore, task allocation in the IoT environment faces a number of challenges due to its scalability, dynamicity, heterogeneity, and the properties that traditionally associated with wireless sensor networks.

Since the distributed systems have become popular as cost-effective alternatives to traditional high-performance computing systems [41-44], in this paper, a hybrid algorithm for task allocation problem in the IoT for minimizing makespan and communication costs among objects is proposed. We combine the well-known Heterogeneous Earliest Finish Time (HEFT) and the Triplet clustering algorithms in a way has been discussed by [45] with one difference: since a lot of nodes interconnected in IoT environment, duplication will cause more overhead, therefore, we avoid the duplication. The contributions of the paper are fourfold:

- Dividing the user application into several tasks which have certain successive restraint relation;
- Using a Directed Acyclic Graph (DAG) to denote the task's dependencies;
- Grouping resources into several categories based on their common features;
- Accomplishing the hybrid algorithm for mapping tasks on appropriate nodes.

2 Literature Review

Sohn et al. [46] have developed a distributed

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scheduling strategy for a network of wireless IoT devices. This strategy aims at maximizing the overall sum rate of the wireless network where centralized coordination is not supported. The approach considers a synchronized slotted structure consisting of two phases: distributed scheduling and communication phase. The algorithm outperforms existing distributed techniques to a considerable extent in a consistent fashion. In addition, the strategy has many benefits from the practical implementation's point of view. The computational load at each node does not increase with the network size and remains manageable. Thus, the proposed strategy is expected for the application to various types of small-sized and low-cost wireless devices.

Furthermore, Abdullah and Yang [47] have introduced QoS awareness task allocation in the IoT by assigning traffic priorities making them energy efficient as well. Messages are categorized into High Priority (HP) and Best Effort (BE) carrying all another non-critical type of data. Sensor nodes are separated into IoT subgroups. Each subgroup has a broker delivering for all nodes and maintaining two queues for HP and BE messages, respectively. Simulation results are shown the efficiency of the algorithm in term of energy and waiting time.

Kim and Ko [48] have proposed a service resource allocation approach for minimizing the data transmissions among user's mobile devices and dealing with the constraints of the environments. They have transformed the resource allocation problem into a variant of the degree-constrained minimum spanning tree problem and applied a genetic algorithm to decrease the time needed to find a near-optimal solution. They have also proposed a fitness function and an encoding method to apply the genetic algorithm. The objective of their research is minimizing data transmissions between gateways. The results showed a high success rate when it is used to find near-optimal solutions. Furthermore, it takes meaningfully less time than the brute force approach.

Moreover, Abdullah and Yang [49] have proposed an energy-aware messaging scheduling mechanism for IoT and where things or sensors are clustered into groups. Each group has a message broker that delivers the messages created from the group to the ultimate receiver of the sensed data. The authors have considered the shortest processing time first algorithm and the energy efficiency is considered in term of routing too. The simulation results have shown the effectiveness and efficiency of the mechanism both in terms of service response time and energy consumption.

Billet and Issarny [50] have presented a mathematical formula of the task mapping problem that captures the varying consumption of resources and various constraints in order to compute a mapping that guarantees the lifetime of the concurrent tasks inside the network. They also have provided a heuristic that allows its resolution in polynomial time. Experiments have shown that the heuristic gives near-optimal solutions and performed directly within the network, without requiring any centralized infrastructure. The algorithm ensures that the task will be performed for a specified lifetime, as a hard constraint during the mapping process.

In addition, Li et al. [51] have introduced the task scheduling problem with multiple processing sequence relation constraints in IoT system. They have proposed a genetic algorithm for solving the task scheduling problem with complex processing sequence relation in IoT systems. Experimental results and comparison with well-known algorithms showed the proposed algorithm minimizes the maximum completion time.

Finally, Colistra et al. [52] have defined the issue related to resource allocation for the deployment of distributed applications in the IoT and described the architecture and functionalities of a relevant middleware that denotes a possible solution to this issue. They have proposed a consensus protocol for the cooperation among network objects in performing the target application. The results have demonstrated that using the proposed protocol causes the network converges to a solution where resources are allocated among nodes.

According to related studies, most of the studies analyzed the energy consumption of resources and load balancing among objects. As shown in Table 1, the researchers are less concerned with the minimizing the makespan. Also, among algorithms for task allocation problem in the heterogeneous system, the HEFT algorithm [53] is the most famous algorithm which produces shorter schedule lengths. Hence, in this paper, a hybrid algorithm is proposed which amalgamate the HEFT and Triplet algorithm [53-54] by clustering tasks and merging the produced clusters to minimize communication overheads.

3 Proposed Method

We aim at presenting how the task allocation problem has been addressed in distributed IoT environment for minimizing makespan and communication costs among objects. The network model, layered IoT architecture, concept of resources in the IoT context and the general task allocation activities that are implemented in this paper are described in the first subsection, whereas the problem statement is addressed in the second subsection, finally, the proposed hybrid algorithm is discussed with details in the third subsection.

3.1 Network Model

The three-layer architecture defines the main idea of the IoT. It was introduced in the early stages of research in this area. It has three layers, namely, the perception, network, and application layers [55]. In this paper, the IoT is considered as a distributed network. Since the middleware is considered as an enabling technology that facilitates the development of distributed applications. Also, in distributed IoT ecosystems, the middleware resides as the second layer in layered IoT architecture. As shown in Figure 1, one of the main functions of IoT middleware is resource management.

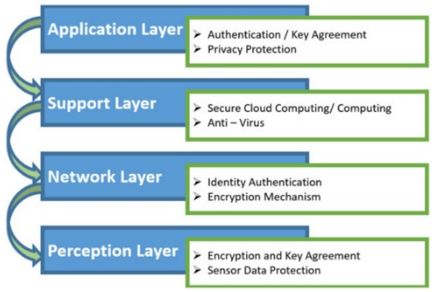

Figure 1. Layered distributed IoT architecture [56]

The implemented key activities for task allocation in the IoT are done in four steps. At first, delivered application to IoT network is modeled as Directed Acyclic Graph (DAG) to denote tasks dependencies that are discussed briefly in the next subsection. Then IoT resources are grouped into several categories based on their common features. A hybrid algorithm for task allocation problem in distributed IoT for minimizing makespan and communication costs among objects is proposed that discussed in detail in the third subsection. Finally, the hybrid algorithm is implemented via the tailored simulator.

3.2 Problem Statement

In this paper, to allocate the submitted tasks on the IoT resources, the user applications are divided into several tasks which have certain successive restraint relation and we use a Directed Acyclic Graph (DAG) to denote tasks dependencies. A DAG is a directed graph consisting of a set of nodes N and a set of edges E where each of edge is in the form of ($i \rightarrow j$), that $i, j \in N$. A node i represents a task and an edge $i \rightarrow j$ represents the communication between i and j. The execution of j cannot begin until the execution of i has been completed, and j becomes a ready node when all of its parents are completed. Given an edge from i to j, i is a parent node of j, and j is a child of i. Figure 3 shows an example of DAG.

3.3 Hybrid Algorithm

The HEFT algorithm produces short schedule lengths [57]. Also, the main concepts of the Triplet algorithm are that the application tasks and the resources in the underline system are grouped into clusters and mapping the tasks clusters onto resources clusters to minimize communication overhead [54]. We amalgamate the HEFT and Triplet algorithms by clustering tasks according to Triplet algorithm with merging the produced clusters to minimize communication overheads, and sorting tasks in each cluster according to rank function of the HEFT [45] with one difference, since a lot of nodes interconnected in the IoT environment, duplication will cause more overhead, therefore, the duplications are ignored. The steps of the proposed algorithm are:

First, a weight is assigned to each node and edge of the graph based on the average computation and communication respectively which is represented in equation (1). Then, the graph is traversed upwards and a rank value is assigned to each node. The ranking function of the node is calculated by the summation of the maximum weight value resulting from all possible immediate successor nodes the weight of an edge, and the rank value of that successor node (i.e., the node has the maximum weight value), as represented in equation (2).

$$W[t_i] = \left(\sum_{j=1}^{j=m} c_j\right) / m \quad \textbf{(1)}$$

Where c_j is the execution time of task i on each resource.

$$r_u(i) = f_1(W_i^0, \ldots, W_i^m, \ldots, W_i^{m-1}) + max_{j \in S_i}\left(f_2(C_{ij}^{00}, \ldots, C_{ij}^{mm'}, \ldots, C_{ij}^{M-1,M-1}) + r_u(j)\right) \quad \textbf{(2)}$$

Where W_m is the computation cost of task i on resource m, $0 < m < M$, S_i is the set of the immediate successor of task i, and $C_{ij}^{mm'}$ is the communication cost between nodes i and j when i executed by resource m and j by resource m', $0 \le m$, $m' < M$. It is assumed that when i and j are executed by the same resource, the communication cost is zero. The function f_1 returns a value which is dependent on the computation cost of a given task on every machine, and f_2 returns a value which is dependent on the communication cost between two given tasks may execute.

In the next step, the application tasks are grouped based on interconnection to minimize communication overhead [54] and IoT resources are grouped into several categories based on their common features, then sorting tasks in each cluster according to a rank function of the HEFT algorithm. Then, we describe some equations; EST (t_i, R_j) and EFT (t_i, R_j) are the earliest execution start time and the earliest execution finish time of task i on resource j, respectively [58]. For the entry task, $EST(t_{enrty}, R_j) = 0$, and for the other tasks, the EST and EFT values are calculated recursively, as shown in (3) and (4). In order to compute the EFT of task i, all immediate predecessor tasks of i must have been scheduled.

$$EST(t_i, R_j) = max\left\{avail[j], max_{t_m \in pred(t_i)}\left(AFT\left(t_m, c_{m,i}\right)\right)\right\} \quad \textbf{(3)}$$

$$EFT(t_i, R_j) = w_{i,j} + EST(t_i, R_j) \quad \textbf{(4)}$$

Where $pred(t_i)$ is the set of immediate predecessor tasks of task *i* and *avail* [*j*] is the earliest time at wich resource *j* is ready for task execution. If t_i is the last assigned task on resource *j*, then *avail* [*j*] is the time that resource *j* completed the execution of the task t_i and it is ready to execute another task when a non-insertion-based scheduling policy is exist. The inner *max* block in the EST equation is the time when all data needed by t_i has arrived at resource *j*. After a task t_i is scheduled on a resource *j*, the earliest start time and the earliest finish time of t_i on a resource *j* is equal the actual start time, AST(t_i), and the actual finish time, AFT(t_i) of task t_i, respectively. After all tasks in a graph are allocated, the algorithm time length is the actual finish time of the exit task t_{exit}. If there are multiple exit tasks and the convention of inserting a pseudo exit task is not applied, the makespan is defined as [59]:

$$makespan = \max\{AFT(t_{exit})\} \quad \textbf{(5)}$$

The objective function of the task allocation problem is to determine the assignment of tasks of a given application to resources such that its schedule length is minimized.

4 Performance Analysis

In this section, a comparative study has been done for analysis of the proposed method, HEFT, and Triplet algorithm by considering the DAG of an application with communication cost (Figure 2). Since the task allocation is allocating the tasks to resources in a proper sequence in which tasks can be executed under problem-specific constraints. The simulation parameters for this problem are *N* tasks, *M* resources, and estimated computation costs and communication costs. In this subsection, an example is represented by considering the DAG of an application with communication cost (Figure 1). In this example, the number of tasks and resources are 10 and 3, respectively. The computation cost for each node is represented in Table 1.

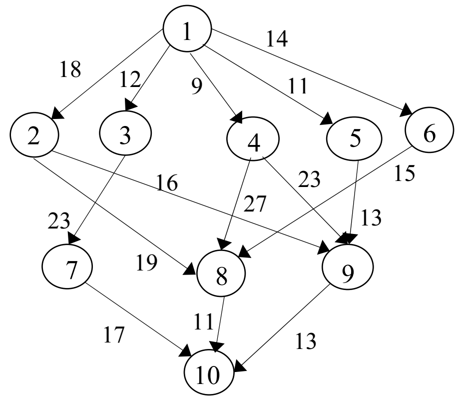

Figure 2. An example of directed acyclic graph [45]

Table 1. Computation cost for each node on three resources [45]

Task	R1	R2	R3
1	37	39	27
2	30	20	24
3	21	21	28
4	35	38	31
5	27	24	30
6	29	37	20
7	22	24	30
8	37	26	37
9	35	31	26
10	33	37	21

The implementation results of the HEFT, Triplet and the proposed algorithm using COOJA simulator are represented in Gantt charts (Figure 3, Figure 4 and Figure 5, respectively). According to the results in Figure 3, the HEFT algorithm has no load balancing between resources. Its makespan is better than the triplet algorithm's makespan, but the triplet algorithm (Figure 4) is better than the HEFT algorithm in terms of load balancing. According to the obtained results in Figure 5, the makespan of the proposed algorithm is not the optimum where is 1.6% greater than the makespan of the HEFT algorithm. Also, random tasks graphs are used for more accurate comparison. Performance evaluation results of the HEFT, the triplet and the proposed algorithm using COOJA simulator are represented in Figure 6 and Figure 7, respectively.

The simulation results represent that the HEFT algorithm, reduces makespan to a greater extent, but the tasks are not distributed evenly among the resources. While the advantage of Triplet algorithm is an equitable distribution of tasks among resources and reducing communication overhead, but does not improve the maximum completion time of tasks. The proposed algorithm reduces communication costs. The makespan of the proposed algorithm is 4.2% less than the Triplet algorithm but is 1.6% greater than the makespan of the HEFT algorithm.

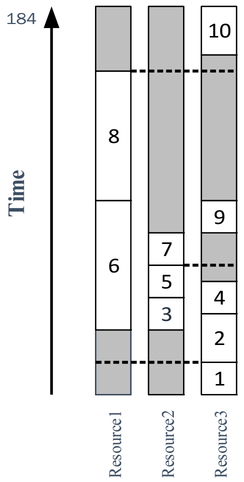

Figure 3. Mapping tasks to resources using HEFT algorithm

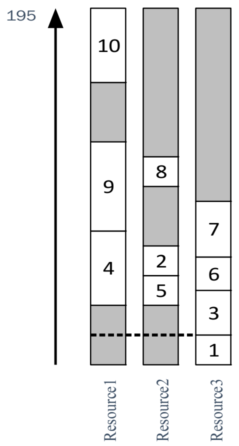

Figure 4. Mapping tasks to resources using Triplet algorithm

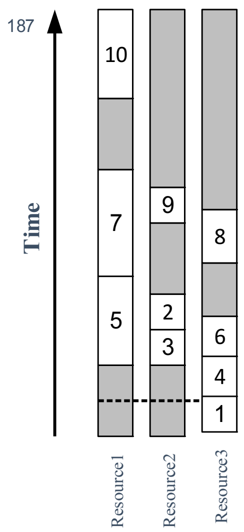

Figure 5. Mapping tasks to resources using the hybrid algorithm.

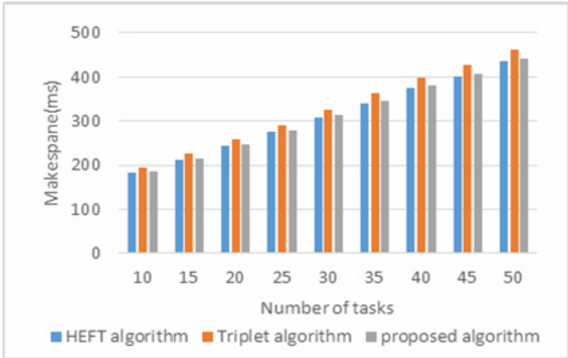

Figure 6. Comparison of makespan of three algorithms

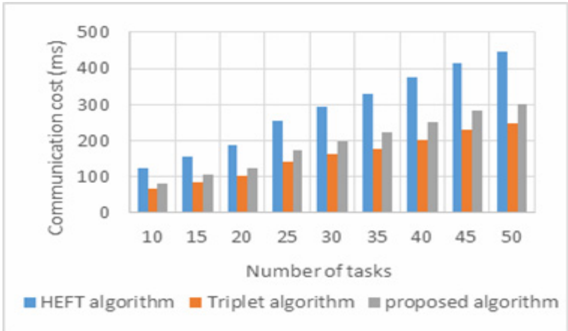

Figure 7. Comparison of the communication costs of three algorithms

5 Conclusion and Future Work

In this paper, a new method for solving the resource allocation problem in distributed IoT is presented for minimizing the makespan and communication costs among tasks. We used a simulator called COOJA. The nodes in COOJA simulator called Mote. This simulation is done using three kinds of motes. To evaluate the performance of the proposed algorithm, a comparative study of the HEFT, Triplet, and the proposed algorithm has been done. According to the results, the HEFT algorithm has no load balancing between resources. Its makespan is better than the triplet algorithm's makespan, but the makespan of triplet algorithm is better than the HEFT algorithm for load balancing. The average makespan of the proposed algorithm is 4.2% fewer than the Triplet algorithm, but it is not the optimum where is 1.6% greater than the makespan of the HEFT algorithm.

Since IoT from low-power sources and sensors are used, energy efficiency is particularly important in the IoT environment, therefore, the fair distribution of tasks between resources is also very important. Whereas, in IoT, objects work together to achieve different goals, so, the best way to allocate resources can be achieved through collaboration objects with each other. This means that objects decide together that a task on which source is allocated. Therefore, in future work, a task allocation problem by working together objects with the goal of equitable distribution of tasks between resources, using well-known heuristic algorithms, can be fertile ground for future research.

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