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研究課題名（和文） Mixed-Clairvoyance Task Offloading and Scheduling in Multi-access Edge Computing Systems: From Combinatorial Optimization to Machine Learning

研究課題名（英文） Mixed-Clairvoyance Task Offloading and Scheduling in Multi-access Edge Computing Systems: From Combinatorial Optimization to Machine Learning

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研究成果の概要（和文）：マルチアクセスエッジコンピューティングシステムにおけるIoTアプリケーションのグラント割り当ておよび送信スケジューリング問題に取り組んでいる。 そのため、Coage of Information（CoI）の加重合計を最小化する整数線形プログラムとして定式化する。 Coageの効率値に従って情報更新が段階的に選択されるアルゴリズムを提案し、達成される近似率を証明する。 シミュレーション結果は、提案法が効果的に情報更新を実行し、サービス予算を活用できることを示しており、それによってさまざまなパラメーター設定の下で既存のソリューションと比較して低いCoIを達成できる。

研究成果の学術的意義や社会的意義
超スマート社会を実現するために、産業、医療、交通、環境など広範囲にわたってAIやIoTなどの技術が応用される。スマートフォンやウェアラブル電子機器などのモバイル機器の普及は、人々の日常生活に変革をもたらしているため、エッジコンピューティング技術の開発がかつてないほどの注目を集めている。本研究では、エッジコンピューティングシステムにおけるIoTアプリケーションのため、効率的なタスクオフローディング及びグラント割り当て、情報鮮度の高いスケジューリングを提案することで、今後の自動運転、AIによるヘルスケア、クロスリアリティ（X-Reality）などのアプリケーションの実現に貢献するものである。

研究成果の概要（英文）：In this research, we address the grant assignment and transmission scheduling (GATS) problem for Internet of Things (IoT) applications in multi-access edge computing (MEC) systems. To this end, we formulate it as an integer linear program (ILP) to minimize a weighted sum of coage of information (CoI). Due to the intractability of the original GATS problem, we transform it to an equivalent problem of the maximization of the number of the eliminated age blocks. Then, we propose the CoI-aware age block elimination (CABEL) algorithm in which information updates are selected progressively according to their coage efficiency (CE) values and prove that the achieved approximation factor depends on the relative service costs and uplink delays. Our simulation results demonstrate that the proposed solution can effectively perform information updates and utilize service budgets, thereby achieving low CoI compared with the existing solutions under various parameter settings.

研究分野： 情報ネットワーク関連

キーワード： エッジコンピューティング　IoT　情報鮮度

１．研究開始当初の背景

(1) Transmission and scheduling are two essential design factors in multi-access edge computing (MEC) systems and Internet of Things (IoT) applications. Existing works have been devoted to MEC systems with clairvoyance, but they mostly neglect the mixed-clairvoyance feature in practical MEC systems.

(2) The timely delivery of IoT data plays a decisive role in various low-latency IoT applications. Despite the existing works in [R1]-[R7] devoted to low-latency service provisioning, how to ensure the timeliness of information updates for IoT remains unclear.

(3) To effectively quantify the mixed-clairvoyance of information updates, information freshness (or age of information (AoI) [R8], [R9]) defined by the period of time elapsed since the generation of the most recently updated information has been recently regarded as a promising performance metric in communication systems. In the extant literature, although [R10]-[R17] leveraged the concept of AoI to measure the timeliness of communication systems, the single-source settings may not well capture the practical situation where multiple IoT devices send information updates to the same destination.

(4) Several works that perform AoI optimization while considering information correlation have been reported in the literature. In [R18]-[R22], the authors explored the effects of the information freshness of correlated information updates, they mostly neglect that 1) CoI is determined by the maximum AoI of all of the involved information updates, 2) the AoI of an IoT device can be influenced by other IoT devices due to the sharing of communication resources, and 3) the information updates of an IoT device may contribute to multiple IoT applications simultaneously.

２．研究の目的

(1) In this research, we focus on addressing the grant assignment and transmission scheduling (GATS) problem for IoT and formulate it as an integer linear program (ILP) to minimize a weighted sum of CoI.

(2) Due to the intractability of the original GATS problem, we transform it to an equivalent problem of the maximization of the number of the eliminated age blocks. Then, we propose the CoI-aware age block elimination (CABEL) algorithm in which information updates are selected progressively according to their coage efficiency (CE) values and prove that the achieved approximation factor depends on the relative service costs and uplink delays.

(3) To evaluate the performance of our proposed solution, we conduct extensive simulations to demonstrate that the proposed solution can effectively perform information updates and utilize service budgets, thereby achieving low CoI compared with the existing solutions under various parameter settings.

３．研究の方法

(1) We consider a grant-based IoT system where an IoT controller manages the information updates of a set $\mathcal{N}$ of IoT devices (see FIGURE 1). The IoT controller is responsible for determining the grant assignment and transmission scheduling for the connected IoT devices and conducting IoT data analytics (e.g., inferring factory productivity in industrial scenarios or assessing the quality of life in urban scenarios) based on the collected information updates. The IoT data analytics is intended for a set $\mathcal{L}$ of IoT applications. Whenever the outcomes of the IoT data analytics give rise to some action changes, they will be forwarded to the corresponding hosts of IoT applications.

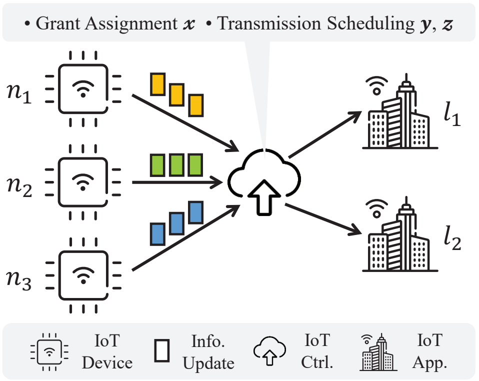

FIGURE 1

(2) The CoI of an IoT application is determined by the maximum AoI of its constituent IoT devices. Clearly, the information updates of an IoT device can be used to improve all the corresponding CoI if they are required for multiple IoT applications. For example, as depicted in FIGURE 2, we see that IoT application l has the constituent IoT devices n_1 and n_2, and hence $C_l(t)$ (the gray lines) is exactly the maximum value of $A_{n_1}(t)$ (purple lines) and $A_{n_2}(t)$ (orange lines) for each time slot t.

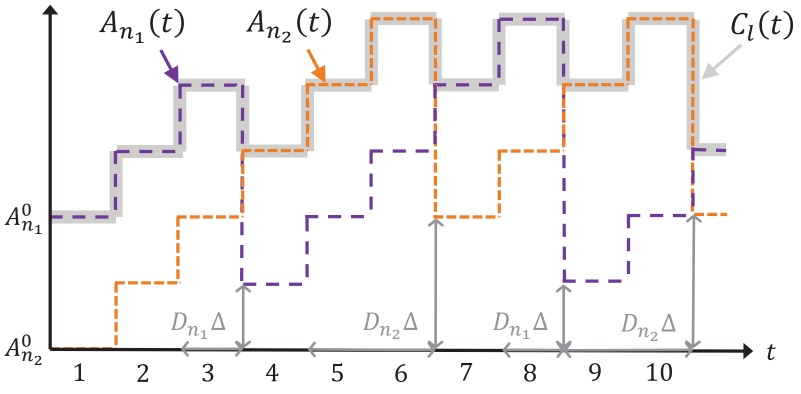

FIGURE 2

(3) Mathematically, our goal is to minimize the weighted sum of CoI among the IoT applications over multiple time slots, where the grant assignment (GA) and transmission scheduling (TS) optimizers are considered. By the fact that each information update can be scheduled only if the corresponding IoT device has been granted, it is evident that the GA and TS optimizers in essence exhibit a causal relationship. Then, we can formulate the GATS problem as an ILP, which has been proved to be NP-hard.

(4) Our algorithmic design principle is to conduct a sequence of information updates. Each information update is carried out to maximize the amount of removed age blocks, and meanwhile minimize the induced service costs as much as possible. To solve the GATS problem, we propose the CoI-aware age block elimination (CABEL) algorithm, which consists of the following five steps: 1) parameter initialization, 2) progressive information updates, 3) CE maximization, 4) parameter updating, and 5) decision output.

4．研究成果

(1) To evaluate the performance of our proposed algorithm (denoted by CABEL), we consider the following comparison schemes that perform information updates differently.

- Zero-Wait (ZW): Each IoT device performs an information update when its previous updated has been acknowledged by the IoT controller. If multiple IoT devices are ready to send at the same time slot, they are randomly selected one by one until the limit of the service budget is reached.
- Round Robin (RR): IoT devices are granted one by one in a deterministic order. At each time slot, multiple IoT devices can be granted if the service budgets are affordable.
- AoI Dependent Random Access (ADRA): Each IoT device performs an information update according to a fixed probability if the current AoI is not less than a predefined threshold. Otherwise, the IoT device stays silent.

(2) FIGUREs 3 and 4 illustrate the profiles of the information updates completed. In FIGURE 3, we see that IoT devices n_2, n_3 and n_6 have no information updates completed (in yellow) because they do not belong to the IoT applications in this case, and all others continually perform information updates (in green). Among the IoT devices with information updates, IoT devices n_9 and n_{10} have less information updates (in lighter green) since both devices can contribute to the CoI of more than one IoT application. Since IoT devices n_9 and n_{10} have less information updates, the number of information updates completed becomes slightly higher than those of the other IoT devices as depicted in FIGURE 4.

(3) FIGUREs 5 and 6 demonstrate how the number of IoT applications affects the CoI performance. It is observed from FIGURE 5 that the average CoI increases with the number of IoT applications because the service budgets become competitive and hence the number of information updates that can be carried out for each IoT application is reduced. When only a few IoT applications coexist in the system, CABEL shows similar performance to those of the other compared schemes. In addition, ZW performs better than RR and ADRA because it performs information updates more aggressively, while CABEL outperforms all other schemes due to its high number of information updates completed (see FIGURE 6). Note that even though RR has comparable information updates completed and service budget utilization (due to its greediness), its deterministic pattern inevitably leads to unwise choices of information updates.

(4) FIGUREs 7 and 8 show how the number of constituent IoT devices in each IoT application influences the information updates. It is observed from FIGURE 7 that CoI increases with increasing number of the constituent IoT devices per IoT application. When the number of constituent IoT devices increases, IoT applications require more information updates (see FIGURE 8) to keep their CoI low. Due to its CoI awareness, CABEL outperforms ZW, RR and ADRA, particularly when the number of the constituent IoT devices increases because the dependency of the constituent information updates is more pronounced.

(5) FIGUREs 9 and 10 depict how uplink delays affect the achieved CoI performance. It is observed that longer uplink delays lead to greater CoI (see FIGURE 9) and lower number of the required information updates (see FIGURE 10). This is because CoI can only be updated to the level of uplink delays whenever an information update has been received, thereby resulting in lower CoI compared with ZW, RR and ADRA.

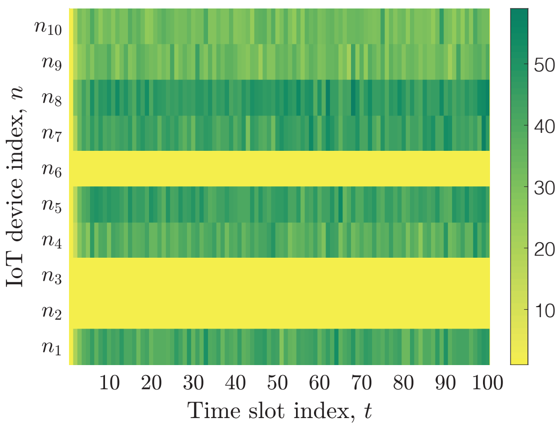

FIGURE 3

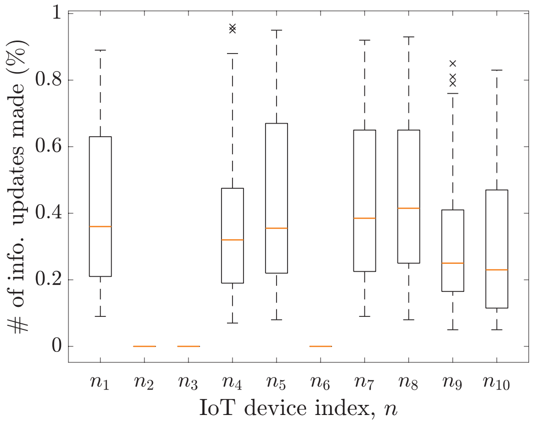

FIGURE 4

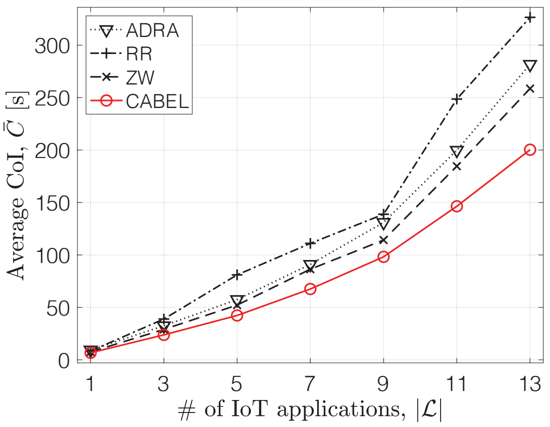

FIGURE 5

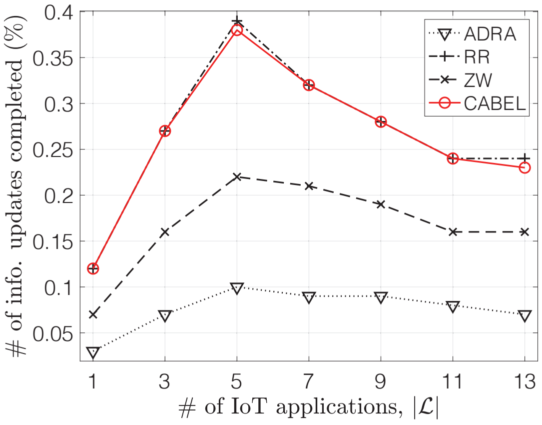

FIGURE 6

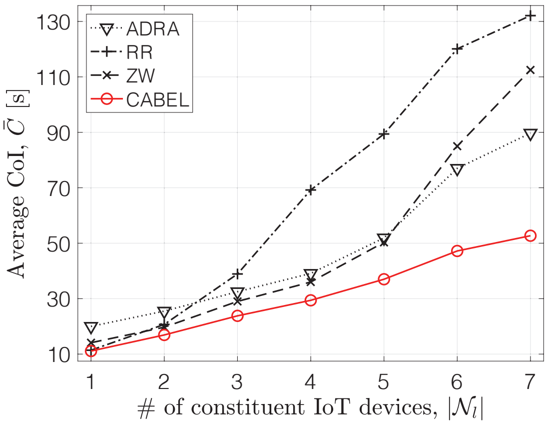

FIGURE 7

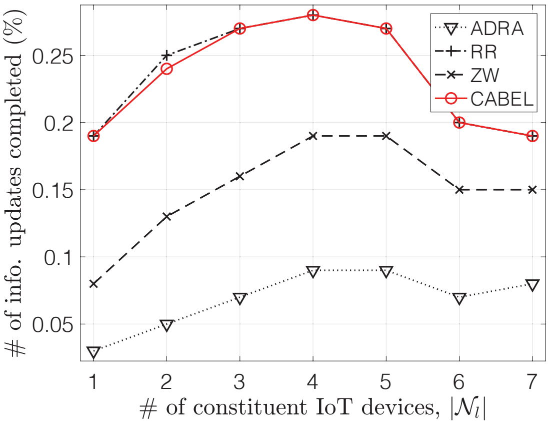

FIGURE 8

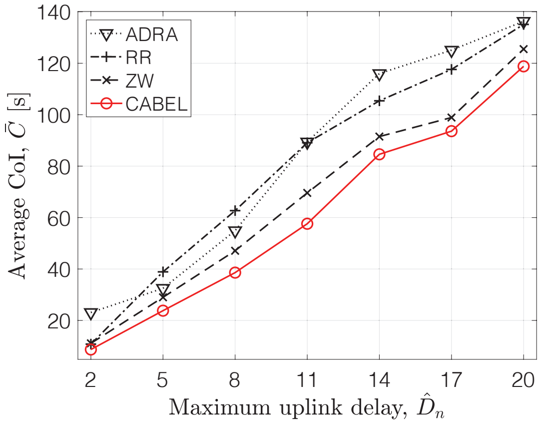

FIGURE 9

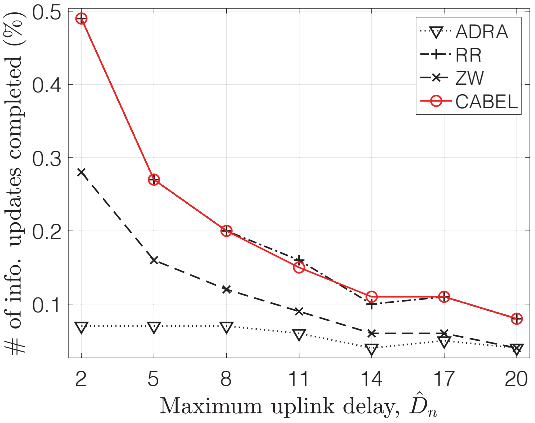

FIGURE 10

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５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　0件）

１．著者名 Chiang Yi-Han、Zhu Chao、Lin Hai、Ji Yusheng	４．巻 3
２．論文標題 Hysteretic Optimality of Container Warming Control in Serverless Computing Systems	５．発行年 2021年
３．雑誌名 IEEE Networking Letters	６．最初と最後の頁 138～141
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LNET.2021.3086489	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Chiang Yi-Han、Wakisaka Sonori、Zhu Chao、Lin Hai、Ji Yusheng	４．巻 11
２．論文標題 Age-Efficient Concurrent Information Update Scheduling in Edge-Native Systems	５．発行年 2022年
３．雑誌名 IEEE Wireless Communications Letters	６．最初と最後の頁 893～897
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LWC.2022.3146908	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Chiang Yi-Han、Chiang Tsung-Wei、Zhang Tianyu、Ji Yusheng	４．巻 7
２．論文標題 Deep-Dual-Learning-Based Cotask Processing in Multiaccess Edge Computing Systems	５．発行年 2020年
３．雑誌名 IEEE Internet of Things Journal	６．最初と最後の頁 9383～9398
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JIOT.2020.3004165	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Zhu Chao、Chiang Yi-Han、Xiao Yu、Ji Yusheng	４．巻 8
２．論文標題 FlexSensing: A QoI and Latency Aware Task Allocation Scheme for Vehicle-based Visual Crowdsourcing via Deep Q-Network	５．発行年 2020年
３．雑誌名 IEEE Internet of Things Journal	６．最初と最後の頁 7625～7637
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/JIOT.2020.3040615	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Chiang Yi-Han、Lin Hai、Ji Yusheng	4．巻 8
2．論文標題 Information Cofreshness-aware Grant Assignment and Transmission Scheduling for Internet of Things	5．発行年 2021年
3．雑誌名 IEEE Internet of Things Journal	6．最初と最後の頁 14435～14446

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オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計7件（うち招待講演　0件／うち国際学会　4件）

1．発表者名 Wakisaka Sonori、Chiang Yi-Han、Lin Hai、Ji Yusheng
2．発表標題 Timely Information Updates for the Internet of Things with Serverless Computing
3．学会等名 IEEE International Conference on Communications (ICC)（国際学会）
4．発表年 2021年

1．発表者名 脇坂園里，江易翰，計宇生，林海
2．発表標題 サーバーレスコンピューティングにおける情報鮮度を考慮したスケジューリング設計
3．学会等名 電気関係学会関西連合大会
4．発表年 2021年

1．発表者名 玉柏昌大，趙亮，江易翰，計宇生，林海
2．発表標題 データ収集における情報鮮度の測定に関する研究
3．学会等名 電気関係学会関西連合大会
4．発表年 2021年

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２．発表標題
健康異常検知における不均一なデータへの連合学習の個別化

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電子情報通信学会総合大会

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2021年

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２．発表標題
Resource Allocation for Multi-access Edge Computing with Coordinated Multi-Point Reception

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IEEE Wireless Communications and Networking Conference (WCNC)（国際学会）

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2020年

１．発表者名
Chiang Yi-Han、Lin Hai、Ji Yusheng、Liao Wanjiun

２．発表標題
Freshness-aware Energy Saving in Cellular Systems with Cooperative Information Updates

３．学会等名
IEEE Global Communications Conference (GLOBECOM)（国際学会）

４．発表年
2020年

１．発表者名
Wakisaka Sonori、Chiang Yi-Han、Lin Hai、Ji Yusheng

２．発表標題
Timely Information Updates for the Internet of Things with Serverless Computing

３．学会等名
IEEE International Conference on Communications (ICC)（国際学会）

４．発表年
2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

—

６．研究組織

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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関