様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　３ 年　 ８ 月 ２０ 日現在

機関番号：２１６０２
研究種目：基盤研究(C)（一般）
研究期間：2018～2020
課題番号：１８Ｋ１１２６９

研究課題名（和文）Development of Novel Access Protocols for Cellular-Based Machine-Type Communications (MTC) Supporting Massive Internet of Things

研究課題名（英文）Development of Novel Access Protocols for Cellular-Based Machine-Type Communications (MTC) Supporting Massive Internet of Things

研究代表者
Ａｎｈ・Ｔ　Ｐｈａｍ（PHAM, T. Anh）

会津大学・コンピュータ理工学部・教授

研究者番号：８０４０４８９６

交付決定額（研究期間全体）：（直接経費）　　3,400,000円

研究成果の概要（和文）：まず、セルラーベースのIoTにおける大規模なアクセス問題に取り組むために、分散キュー（DQ）メカニズムに基づく新たなアクセスプロトコルを提案した。　次に、デバイスの大部分が高密度のスモールセルでカバーされているため、スモールセル基地局（SBS）が事前の送信ステップ中にMTDの代表として機能し、シグナリング中のチャネルの負荷を軽減できるという事実を利用した。最後に、エネルギー消費を抑えつつ規制係数と平均規制時間の両方を制御するDueling Deep Q-Network（DNN）ベースのACBソリューションを提案し、これが大幅に低いエネルギーコストで超低遅延性能を達成できることを確認した。

研究成果の学術的意義や社会的意義
私達は5Gモバイルネットワークによってサポートされるモノのインターネット（IoT）の時代で、大規模なマシン通信（MTC）デバイス用のランダムアクセスプロトコルの設計と開発に取り組んでいる。 大規模なIoTをサポートする5Gモバイルネットワークでは、セルあたり3万MTCデバイスに対応する機能を備えたモバイルセルを想定する必要がある。 私達はスマートシティアプリケーションの負荷パターンに典型的な、膨大な量（数万の同時オーダー）の異なる優先度で規則的または緊急のトラフィックをサポートできるアクセスプロトコルの新しい設計とアーキテクチャを提案している。

研究成果の概要（英文）：The project has three main achievements. First, we proposed a novel access protocol based on the distributed queue (DQ) mechanism to tackle the massive access issue in cellular-based IoT. We also built a simulation model to validate the analytical model and the effectiveness of the proposed protocol. Second, we exploited the fact that a significant portion of devices is covered by densely deployed small-cells such that a small-cell base station (SBS) may act as a representative for its MTDs during the preamble transmission step to reduce the load on signaling channels. Finally, we proposed a Dueling Deep Q-Network (DNN)-based dynamic ACB solution that explicitly considered energy consumption and controlled both the barring factor and the mean barring time. We confirmed that the proposed method could achieve a good delay performance at a significantly lower energy cost. Furthermore, our proposed scheme could efficiently realize the tradeoff between access delay and energy consumption.

研究分野：情報学

キーワード：massive IoT　M2M Communications　Random Access Protocol　Distributed Queue　Access Class Barring　RFID

１．研究開始当初の背景

The next-generation mobile network, also known as the fifth generation (5G) mobile network, is expected to provide infrastructure for new communication paradigm - the Internet of Things (IoT). One of the most important visions of the IoT is the design and implementation of smart cities [1], which can be defined as the city that supports a wide range of smart applications, for example:

- *Smart grids, smart metering*: this service is the most feasible one that offers the capability to monitor smart grids. It has been on trial in a number of cities in Japan.
- *City automation, transportation*: smart parking system, traffic monitoring, real-time travel and route updates, smart/shared bicycle, smart garbage bins in a city.
- *eHealth (wearable devices)*: offers health condition updates by various sensors in wearable devices.
- *Surveillance and security*: secure access and monitoring in city buildings and neighborhoods.
- *Infrastructure and resource management*: connection to sensor networks that monitor various infrastructure of a city, such as load sensing for critical infrastructures, fire monitor of historical sites and, to some extent, agricultural management (smart farms).

These smart applications require a new kind of communications over the mobile networks that enable ubiquitous connectivity between autonomous devices without or with minimal human interaction, which is called machine-type communications (MTC) devices; and the communication between one or multiple MTCs with severs is also known as Machine-to-machine communications (M2M) [2].

There are two main approaches currently being taken to implement MTC over mobile networks (or cellular-based MTC network) - as depicted in Fig. 1. The first choice involves organizing MTC devices in a so-called MTC area network using short-range wireless standards, such as Bluetooth, Wi-Fi. These MTC area networks are then connected to a mobile Base Station (BS) via MTC gateways equipped with Subscriber Identity Modules (SIMs). In this case, the gateways act as User Equipment (UE) from mobile network perspective. The second option turns every single MTC device into a UE with direct communications to the BS, and thus, is more suitable for ubiquitous outdoor deployment. In addition, this approach not only eliminates the need for deployment of MTC-specific base stations, but also readily provides IP-native connectivity and thus, greatly facilitates the penetration of MTC into the market. This proposal tackles with the design and implementation issues of the second approach.

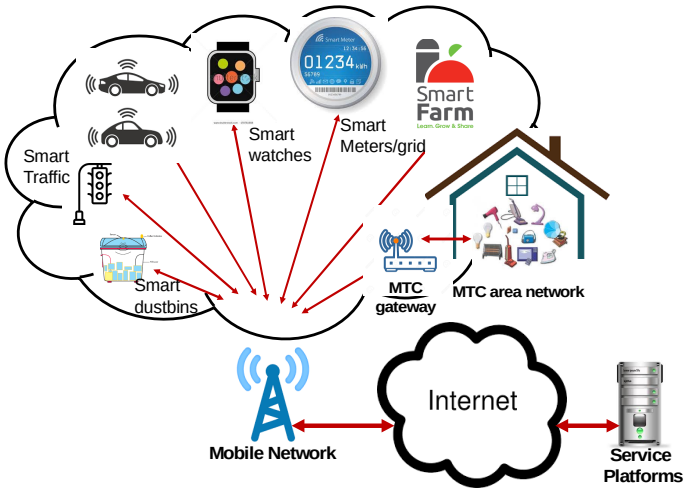

Fig. 1: Model of cellular-based MTC network.

２．研究の目的

One of the most challenging issues in the cellular-based MTC network design is the massive population of MTC devices (massive MTC or mMTC) and their periodic network access patterns (for example, when tens of thousands of smart meters reset, become active and try to access the network simultaneously), which may cause the Random-Access Channel (RACH) of current mobile network (LTE) to break down [3]. In the context of smart cities, it is projected that the cellular-based mMTC to have the capability to 30K devices per cell; and for the 5G, a 10 times higher capacity, i.e., 300K devices

per cell, should be envisioned, according to 3GPP studies [4]. In addition, recent report from Cisco and Ericson reveals that, as many as 50 billion MTC devices are expected to be connected to the IoT network [5].

Development of novel and more effective access protocols for mMTC is therefore the key factor for the successful implementation of cellular-based IoT. The main purpose in this research is centered around the proposal of novel access protocols that could support mMTC within the framework of 5G mobile networks and beyond.

３．研究の方法

The goal of the project is the development of novel access protocol for mMTC in 5G mobile network. The novel protocol must comply with two key requirements. First, it should be able to accommodate tens of thousands simultaneous arrivals with minimal blocking and controllable delay. Second, the access protocol is expected to support both periodic/massive and emergency traffics with different levels of priority, which are two typical load patterns of the smart city applications.

To achieve the goal, methods for project implementation therefore include protocol design, analytical modelling and system's simulation constructions. In particular, we organize the project implementation into four major themes, including (1) insightful investigation, definitions of the requirements of mMTC access protocol, (2) study of mMTC traffic modelling taking into account its various unique features, (3) analytical models and simulation framework of proposed protocols, and (4) investigation of various improvement techniques that lead to the achievement of the above-mentioned goal of the proposal.

４．研究成果

In summary, the project results can be reflected in four main achievements, as follows.

First, the Long-Term Evolution (LTE) cellular networks are the main enabler for the massive Machine-Type Communications service and must therefore handle a huge number of Machine-Type Devices (MTDs). To control the number of devices that are allowed to contend on the Physical Random Access Channel (PRACH), the Group Paging scheme that divides the MTDs into smaller groups and let the network sequentially trigger the groups has been studied. However, since the number of PRACH preambles is limited, the group's size must be kept relatively small compared to the MTD population. In the first achievement, we exploit the possibility that a significant portion of MTDs is also covered by densely deployed small-cells such that a small-cell base station (SBS) may act as a representative for its MTDs during the preamble transmission step to reduce the load on PRACH. Once the SBS succeeds, its MTDs then contend locally to send their own signaling messages on the corresponding reserved uplink resources. Computer simulations show that the manageable group size can be significantly increased at a reasonable cost on the Physical Uplink Shared Channel. A theoretical model to quickly predict the effect of the ratio of MTDs that are under the coverage of the SBSs is also derived and verified.

Secondly, we propose a novel access protocol based on the distributed queue (DQ) mechanism to effectively tackle the massive access issue in the cellular-based IoT. A new method to avoid the DQ's inherent over-division problem by letting the base station first roughly probes the number of colliding devices in a random-access opportunity. We also develop an analytic model to accurately estimate the average access delay of the proposed protocol in the massive scenarios. We then build a simulation model to validate the analytic model as well as the effectiveness of the proposed protocol in comparison with the LTE standard and conventional DQ access schemes.

Thirdly, we propose a novel concept of Virtual Small Cells (VSCs) to solve the random-access overload issue in the group-paging process caused by the massive arrivals. The proposed VSC-based RAP is designed based on the group-based access manner and an adaptive access barring algorithm, which efficiently controls the access rate in each VSC during the paging process. Computer simulation shows that, in the context of massive MTCs, the proposed VSC-based scheme can significantly outperform the conventional GP in terms of success access rate and average delay of successfully

accessed devices.

Finally, we proposed a Dueling Deep Q-Network (DNN)-based dynamic ACB solution that explicitly considered energy consumption and controlled both the barring factor and the mean barring time. We confirmed that the proposed method could achieve a good delay performance at a significantly lower energy cost. Furthermore, our proposed scheme could efficiently realize the tradeoff between access delay and energy consumption.

The result of the project has been disseminated in many different forums, including publications in reputable transactions, journals, international conferences, and in the public domain of the Internet (project website). In total, the result of this 3-year project has been published in eight (08) journal articles, including one (01) under review, and four (04) conference papers. All publications are accessible in the public domain for the more detail result of the project.

<引用文献>

① V. Angelakis, et al., “Designing, Developing, and Facilitating Smart Cities: Urban Design to IoT Solutions”. *Springer*, Jan. 2017.
② A.W. Hamouda et al., "Next generation M2M cellular networks: challenges and practical considerations," in *IEEE Comm. Magazine*, vol. 53, pp. 18-24, Sep. 2015.
③ Laya et al., “Is the Random Access Channel of LTE and LTE-A Suitable for M2M Commun.? A Survey of Alternatives,” *IEEE Commun. Surveys Tuts.,* vol. 16, pp. 4-16, Dec. 2013.
④ Dohler Mischa et al., “5G Mobile and Wireless Communications Technology”, *Cambridge University Press*, 2016.
⑤ Cellular Networks for Massive IoT. Ericsson white paper 2016.

５．主な発表論文等

〔雑誌論文〕　計8件（うち査読付論文　8件／うち国際共著　8件／うちオープンアクセス　5件）

１．著者名 Bui Anh-Tuan H.、Nguyen Chuyen T.、Thang Truong Cong、Pham Anh T.	４．巻 68
２．論文標題 A Comprehensive Distributed Queue-Based Random Access Framework for mMTC in LTE/LTE-A Networks With Mixed-Type Traffic	５．発行年 2019年
３．雑誌名 IEEE Transactions on Vehicular Technology	６．最初と最後の頁 12107～12120
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TVT.2019.2949024	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 Bui Anh-Tuan H.、Nguyen Chuyen T.、Thang Truong C.、Pham Anh T.	４．巻 6
２．論文標題 Design and Performance Analysis of a Novel Distributed Queue Access Protocol for Cellular-Based Massive M2M Communications	５．発行年 2018年
３．雑誌名 IEEE Access	６．最初と最後の頁 3008～3019
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2017.2786678	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Hoang Linh T.、Pham Anh T.、Nguyen Chuyen T.	４．巻 6
２．論文標題 Design and Analysis of a Novel Time- and Energy-Efficient <inline-formula> <tex-math notation="LaTeX">M </tex-math> </inline-formula>-Ary Tree Protocol With Collision Window for Dense RFID Systems	５．発行年 2018年
３．雑誌名 IEEE Access	６．最初と最後の頁 58549～58563
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2018.2874679	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Nguyen Chuyen T.、Nguyen Van-Dinh、Pham Anh T.	４．巻 8
２．論文標題 Tag Cardinality Estimation Using Expectation-Maximization in ALOHA-Based RFID Systems With Capture Effect and Detection Error	５．発行年 2019年
３．雑誌名 IEEE Wireless Communications Letters	６．最初と最後の頁 636～639
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/LWC.2018.2890650	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 Pham Huong-Giang T.、PHAM Quoc-Viet、Pham Anh T.、Nguyen Chuyen T.	4．巻 8
2．論文標題 Joint Task Offloading and Resource Management in NOMA-Based MEC Systems: A Swarm Intelligence Approach	5．発行年 2020年
3．雑誌名 IEEE Access	6．最初と最後の頁 190463～190474
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2020.3031614	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Bui Anh-Tuan H.、Pham Anh T.	4．巻 8
2．論文標題 Deep Reinforcement Learning-Based Access Class Barring for Energy-Efficient mMTC Random Access in LTE Networks	5．発行年 2020年
3．雑誌名 IEEE Access	6．最初と最後の頁 227657～227666
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2020.3045811	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Bui Anh-Tuan H.、Nguyen Chuyen T.、Hayashi Takafumi、Pham Anh T.	4．巻 9
2．論文標題 Small-Cell Assisted Group Paging for Massive MTC in LTE Networks: Design and Analysis	5．発行年 2021年
3．雑誌名 IEEE Access	6．最初と最後の頁 40933～40949
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/ACCESS.2021.3064321	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Hoang Linh T.、Bui Anh-Tuan H.、Nguyen Chuyen T.、Pham Anh T.	4．巻 NA
2．論文標題 A Slotted Access-Inspired Group Paging Scheme for Resource Efficiency in Cellular MTC Networks	5．発行年 2021年
3．雑誌名 IEEE Transactions on Green Communications and Networks	6．最初と最後の頁 Under Review
掲載論文のDOI（デジタルオブジェクト識別子） なし	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

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　4件）

１．発表者名
Anh-Tuan H. Bui, Chuyen T. Nguyen, Truong C. Thang, and Anh T. Pham

２．発表標題
Free Access Distributed Queue Protocol for Massive Cellular-based M2M Communications with Bursty Traffic

３．学会等名
IEEE 88th Vehicular Technology Conference (VTC2018-Fall)（国際学会）

４．発表年
2018年

１．発表者名
Linh Hoang, Chuyen T. Nguyen, and Anh T. Pham

２．発表標題
A Novel Time- And Energy-Efficient Tag Identification Protocol in Dense RFID Systems

３．学会等名
IEEE 7th International Conference on Communications and Electronics (ICCE 2018)（国際学会）

４．発表年
2018年

１．発表者名
Linh T. Hoang, Anh-Tuan H. Bui, Chuyen T. Nguyen, and Anh T. Pham

２．発表標題
A Novel Virtual Small Cell-Based Group-Paging Scheme for Massive MTCs over LTE Networks

３．学会等名
2020 IEEE/CIC International Conference on Communications in China (ICCC)（国際学会）

４．発表年
2020年

１．発表者名
Luu X. Nguyen, Chuyen T. Nguyen, Vu X. Phan, and Anh T. Pham

２．発表標題
A Novel User Pairing Scheme for Non-orthogonal Multiple Access Backscatter Communication

３．学会等名
2020 International Conference on Communications and Electronics (ICCE)（国際学会）

４．発表年
2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

Kahenhi Project - 18K11269 http://www.u-aizu.ac.jp/labs/ce-cc/18K11269/

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究協力者	林　隆史 (HAYASHI Takafumi) (20218580)	日本大学・工学部 情報工学科・教授 (32665)	
研究協力者	チョオン　コンタン (Truong CongThang) (40622957)	会津大学・コンピュータ理工学部・上級 准教授 (21602)	

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