Game-Theoretic Distributed Algorithm for Virtual TDM-PON Formulation to Realize Adaptive Data Transmission in C-RANs

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Abstract: We study the problem of building virtual base stations (vBS') adaptively in the TWDM-PON-based C-RAN, and developed a distributed algorithm based on the game-theoretic approach to formulate virtual TDM-PONs. We prove the existence of Nash Equilibrium (NE) points in the game and verify that the proposed algorithm can converge to an NE point quickly.

OCIS codes: (060.4250) Networks; (060.4264) Networks, wavelength assignment.

1. Introduction

Cloud radio access network (C-RAN) has been considered as a promising solution to fix the issues with today's radio access networks (RANs), *e.g.*, high energy consumption due to statically-allocated hardware base stations (BS'), low network capacity adaptivity to highly dynamic traffic, and inefficient BS utilization under traffic fluctuation [1]. Specifically, a BS in traditional RANs consists of two parts: 1) the baseband unit (BBU) for baseband processing, and 2) the remote radio head (RRH) for transmitting/recieving radio signals. Note that, BBU and RRH are located in the same cell site and they are dedicated to each other. In contrast, C-RAN moves BBUs to a cloud-based BBU pool while leaves RRHs in the cell sites, which breaks up the static and rigid mapping among the BBUs and RRHs and greatly improves the system adaptivity. Hence, a virtual BS (vBS), which uses the processing capacity allocated from the BBU pool, can be dynamically instantiated to process the radio signals from/to a particular RRH. Although C-RAN brings a lot of benefits in cost, capacity and flexibility over the traditional RANs, there are some technical challenges that have to be addressed before it can be widely deployed by mobile operators. For instance, as the BBU pool is located separately from the RRHs in the cell sites, transmitting large amounts of baseband sampling data between them in real time with low latency would be not only important but also necessary. Fortunately, we can leverage the time-and-wavelength-division-multiplexing based passive optical networks (TWDM-PONs) to support the data transmission mentioned above, due to its abundant bandwidth capacity and relatively low energy consumption [2].

Fig. 1 shows the architecture of a TWDM-PON-based C-RAN. In the central office, the cloud-based BBU pool uses an array of line-cards (LCs) in the optical line terminal (OLT) to connect to the RRHs through a TWDM-PON. Here, each LC is equipped with a pair of burst-mode transmitter/reciever (B-Tx/B-Rx) and a media access control (MAC) module. Note that, the LCs use different wavelength channels to communicate with the optical network units (ONUs) that connect to the RRHs. Then, the wavelength-division multiplexer/demultiplexer (MUX/DEMUX) collects the downstream signals from the LCs to forward to the ONUs, and it also directs the upstream signals from the ONUs to their LCs according to the wavelengths. On the other hand, in each cell site, the RRH connects to an ONU, which has a pair of tunable B-Tx/B-Rx [3] and an MAC module. Meanwhile, there is a splitter to bridge the optical signal in between the central office and the cell sites. Note that, as each LC uses a distinct wavelength channel, we can treat the network system that consists of it and all the ONUs that uses its wavelength channel as an independent TDM-PON. Moreover, if we assume that the ONUs are colorless and can register to different LCs at will, the idea of virtual TDM-PON (vTDM-PON) can be introduced to formulate vBS' dynamically according to the traffic demands from the RRHs [4, 5]. Specifically, each vTDM-PON is composed of an LC that connects to the BBU pool, several ONUs that each hosts a RRH, and a dedicated wavelength channel that carries the communications between the LC and the

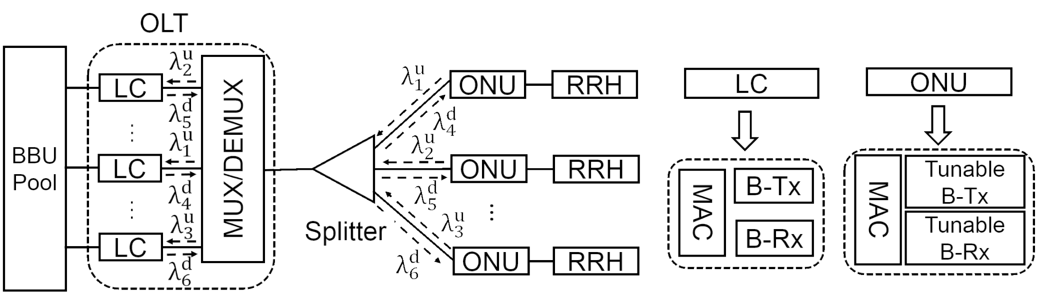

Fig. 1. Architecture of TWDM-PON-based C-RAN.

ONUs in a TDM manner. Previously, people have investigated how to build vBS' adaptively in the TWDM-PON-based C-RAN by formulating vTDM-PONs and allocating processing capacity in the BBU pool in [4, 5]. They considered traffic consolidation and energy saving and designed several centralized algorithms for the vTDM-PON formulation. However, even though the centralized algorithms have been proven to be effective, putting all the decision making in the central office might increase the complexity of problem solving and cause unwanted network control overheads.

In this work, we also consider the problem of building vBS' adaptively in the TWDM-PON-based C-RAN, but try to develop a distributed algorithm to facilitate the vTDM-PON formulation. More specifically, we consider the scenario in which the RRH's ONU in each cell site can choose to register to an arbitrary LC (*i.e.*, a vTDM-PON) based on its knowledge on the C-RAN, leverage the game-theoretic approach to formulate the problem as a weighted potential game, prove the existence of Nash Equilibrium (NE) point(s) in the game, and propose a distributed algorithm for each ONU to choose its vTDM-PON intelligently based on the NE point(s). The simulation results indicate that with the proposed algorithm, the ONUs can change their vTDM-PON registration strategies adaptively and make the network operation converge to an NE point quickly.

2. Game Scenario of vTDM-PON Formulation

We denote the set of available vTDM-PONs as $L = \{1, 2, \cdots, m\}$, each of which corresponds to a LC operating on a distinct wavelength channel. The traffic processing capacity of each vTDM-PON is assumed to be identical as μ. The set of cell sites that each consists of a RRH connecting to an ONU is denoted as $C = \{1, 2, ..., n\}$. We define the traffic loads of the cell sites as $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda_n\}$. Then, as the RRH's ONU in each cell site can choose to register to an arbitrary vTDM-PON based on its knowledge on Λ, we model the registration process as a noncooperative game among the ONUs. In the game, each ONU $i \in C$ is a player whose strategy profile is $S_i = L = \{1, 2, \cdots, m\}$, which means that the ONU can register to any available vTDM-PON. Hence, if we consider all the ONUs, their overall strategy profile is $S = S_1 \times ... \times S_i ... \times S_n$, based on which we can define the utility function of ONU i as

$$\Phi_i(\gamma) = \alpha \cdot \left(\mu - \sum_{j=1}^{n} I(s_j, s_i) \cdot \lambda_j\right) - f(s_i), \tag{1}$$

where $\gamma = (s_1, ..., s_i, ..., s_n) \in S$ is a specified vTDM-PON registration strategy, s_i is the strategy of ONU i, α is a positive constant, and $f(\cdot)$ is a non-decreasing and positive price function of vTDM-PON's ID s_i. Here, $I(s_j, s_i)$ is a flag function to indicate whether ONUs i and j register to the same vTDM-PON, if yes, $I(s_j, s_i) = 1$, and 0 otherwise. Hence, even not exactly the same, the term $\left(\mu - \sum_{j=1}^{n} I(s_j, s_i) \cdot \lambda_j\right)$ is negatively related to the average traffic processing delay of ONU i, if it selects to register to vTDM-PON s_i. Note that, we use function $f(\cdot)$ to encourage the ONUs to select the first a few vTDM-PONs for consolidating vTDM-PON utilization and reducing energy consumption.

Definition A game $G = < C, \{S_i : i \in C\}, \{\Phi_i : i \in C\} >$ is called a **weighted potential game**, if there exists a potential function P such that for any $i \in C$, $(s_i, s^{-i}) \in S_i$, and $(s_i^*, s^{-i}) \in S_i$, we have

$$\Phi_i(s_i, s^{-i}) - \Phi_i(s_i^*, s^{-i}) = \omega_i \cdot \left(P(s_i, s^{-i}) - P(s_i^*, s^{-i})\right), \tag{2}$$

where we use s^{-i} to denote the strategies of all the players except for player i, $s_i^* \in S_i$ is a different strategy from s_i, and ω_i is the weight constant. It has been proved that every finite weighted potential game has at least one NE point [6].

Theorem 1. *The vTDM-PON registration game is a finite weighted potential game.*

Proof. First, we define the function P as

$$\begin{aligned} P(\gamma) &= -\frac{\alpha}{2} \cdot \sum_{j=1}^{n} \sum_{k=1}^{n} \lambda_k \cdot \lambda_j \cdot I(s_j, s_k) - \sum_{j=1}^{n} \lambda_j \cdot f(s_j) \\ &= -\frac{\alpha}{2} \Big(\sum_{j \neq i} \sum_{k \neq i} \lambda_k \cdot \lambda_j \cdot I(s_j, s_k) + \lambda_i^2 \Big) - \sum_{j \neq i} \lambda_j \cdot f(s_j) - \alpha \cdot \sum_{j \neq i} \lambda_i \cdot \lambda_j \cdot I(s_j, s_i) - \lambda_i \cdot f(s_i). \end{aligned} \tag{3}$$

Then, we have

$$\begin{aligned} P(x, s^{-i}) - P(y, s^{-i}) &= \Big(-\alpha \cdot \sum_{j \neq i} \lambda_i \cdot \lambda_j \cdot I(s_j, x) - \lambda_i \cdot f(x) \Big) - \Big(-\alpha \cdot \sum_{j \neq i} \lambda_i \cdot \lambda_j \cdot I(s_j, y) - \lambda_i \cdot f(y) \Big) \\ &= \lambda_i \cdot \Big(\Big(\alpha \cdot \Big(\mu - \sum_{j=1}^{n} \lambda_j \cdot I(s_j, x) \Big) - f(x) \Big) - \Big(\alpha \cdot \big(\mu - \sum_{j=1}^{n} \lambda_j \cdot I(s_j, y) \big) - f(y) \Big) \Big) \\ &= \lambda_i \cdot \left(\Phi_i(x, s^{-i}) - \Phi_i(y, s^{-i}) \right). \end{aligned} \tag{4}$$

Finally, by combining Eqs. (3)-(4), we get

$$\Phi_i\left(x, s^{-i}\right) - \Phi_i\left(y, s^{-i}\right) = \frac{1}{\lambda_i} \cdot \left(P\left(x, s^{-i}\right) - P\left(y, s^{-i}\right)\right). \quad (5)$$

Hence, we prove that the vTDM-PON registration game is a weighted potential game whose potential function is P. Moreover, since the game has finite strategy profiles, it is finite and thus has at least one NE point. □

Therefore, based on *Theorem* 1, we design the following distributed vTDM-PON registration algorithm:
Step 1: Initialize the vTDM-PON registration strategy profile $S = S_1 \times \ldots \times S_i \ldots \times S_n$.
Step 2: The ONUs try to finalize their registration strategies by iteration. In each iteration, only one ONU updates its strategy, and the overall strategy profile is updated according to $\underset{\gamma=(s_i^*, s^{-i})}{\operatorname{argmax}} \left\{\Phi_i\left(s_i^*, s^{-i}\right)\right\}$.
Step 3: The iterations stop when the strategy profile does not change anymore, *i.e.*, the algorithm finds an NE point.

3. Performance Evaluation

We design simulations to evaluate the performance of the proposed vTDM-PON registration algorithm. We assume that there are 8 available vTDM-PONs and 8 cell sites. For simplicity, we have the price function as $f(s_i) = s_i$. Fig. 2(a) shows the convergence performance of the proposed algorithm with $\alpha = 0.5, 1, 1.5$, and we can see that the algorithm can converge to the NE point within a small number of iterations. Besides, it is interesting to notice that even though α affects the final value of the potential function, it has no influence on the convergence speed. Fig. 2(b) shows the effects of α on the average traffic processing delay of the vTDM-PONs and on the number of active vTDM-PONs (*i.e.*, vTDM-PONs with at least one registered ONUs). When α is relatively small, Eq. (1) determines that the cost for the ONUs to register to an empty vTDM-PON is high, and thus they tend to share the vTDM-PONs, leading to relatively long average delay. However, as α increases, the number of active vTDM-PONs also increases and hence the average delay decreases. These results verify the effectiveness of α on balancing the tradeoff between the average delay in vTDM-PONs and the number of active vTDM-PONs. Fig. 2(c) shows the effects of the total traffic load on the average traffic processing delay and on the number of active vTDM-PONs. As expected, the average delay and the number of active vTDM-PONs increase with the total traffic load. Basically, when the traffic load is increasing, the ONUs tend to register to empty vTDM-PONs to decrease their average traffic processing delays.

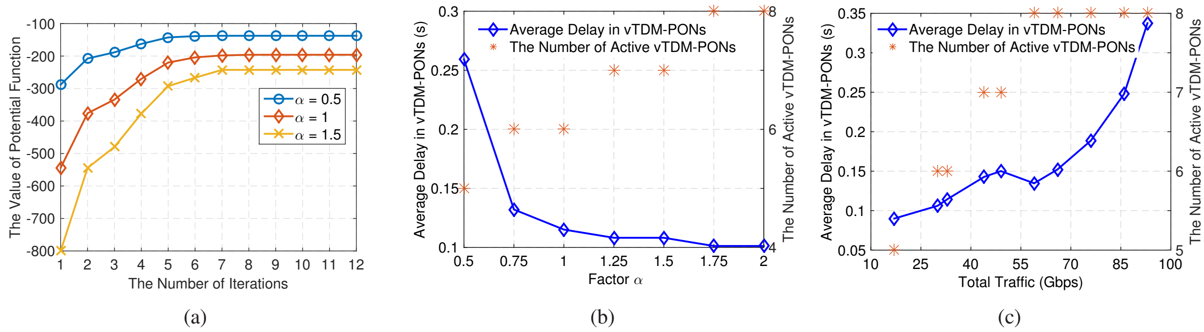

Fig. 2. Results on (a) convergence performance of the proposed algorithm, (b) effects of α on average delay and number of active vTDM-PONs, and (c) effects of total traffic load on average delay and number of active vTDM-PONs.

4. Conclusion

We considered the problem of building vBS' adaptively in the TWDM-PON-based C-RAN, and developed a distributed algorithm based on the game-theoretic approach to facilitate the vTDM-PON formulation. The simulation results indicated that with the proposed algorithm, the ONUs could change their vTDM-PON registration strategies intelligently and make the network operation converge to the Nash Equilibrium point quickly.

References

[1] China Mobile Research Institute, "C-RAN: the road towards green RAN," *White Paper*, Oct. 2011.
[2] D. Iida, *et al.*, "Dynamic TWDM-PON for mobile radio access networks," *Opt. Express*, vol. 21, pp. 26209–26218, Oct. 2013.
[3] H. Nakamura, *et al.*, "40Gbit/s-class-λ-tunable WDM/TDM-PON using λ-selectable B-Tx and cyclic AWG router for flexible photonic aggregation networks," *Proc. of ECOC 2012*, paper Tu.4.B.3, Sept. 2012.
[4] R. Wang, *et al.*, "Energy saving via dynamic wavelength sharing in TWDM-PON," *IEEE J. Select. Areas Commun.*, vol. 32, pp. 1566–1574, Aug. 2014.
[5] X. Wang, *et al.*, "Green virtual base station in optical-access-enabled cloud-RAN," *Proc. of ICC 2015*, pp. 5002–5006, June. 2015.
[6] D. Monderer, *et al.*, "Potential games," *Game Econ. Behav.*, pp. 124–143, 1996.