Game-Assisted Distributed Decision-Making to Build Virtual TDM-PONs in C-RANs Adaptively

Lipei Liang, Wei Lu, Massimo Tornatore, *Senior Member, IEEE*, Zuqing Zhu, *Senior Member, IEEE*

***Abstract*—Although it is a promising solution for next-generation radio access networks (RANs), cloud RAN (C-RAN) still faces a few technical challenges due to the separated locations of the cloud-based baseband unit (BBU) pool and of the remote radio heads (RRHs). Fortunately, time-and-wavelength-division-multiplexing based passive optical networks (TWDM-PONs) can efficiently bridge the communications between the BBU pool and the RRHs. In this work, we address the problem of formulating virtual TDM-PONs (vTDM-PONs) adaptively in a TWDM-PON-based C-RAN. However, instead of relying on a centralized approach, we develop algorithms that can work in a distributed manner. Specifically, we consider a scenario in which the optical network unit (ONU) of each RRH has the initiative to choose a proper vTDM-PON to register to based on its knowledge on the C-RAN. We formulate game theoretic models for the vTDM-PON formation for both the static and dynamic operation of a C-RAN, then transform the games into weighted potential games, and therefore prove the existence of Nash equilibrium (NE) points in the games. Moreover, we propose a distributed algorithm that can converge to the NE point(s) to enable each ONU to choose its vTDM-PON intelligently. As comparison, we formulate a centralized mixed-integer linear programming (MILP) model to provide the optimum vTDM-PON formation solution. Simulation results confirm the effectiveness of the design of the proposed game models and the effectiveness of the proposed distributed algorithm.**

***Index Terms*—Cloud radio access network (C-RAN), Virtual time-division-multiplexing based passive optical network (vTDM-PON), Fronthaul, Potential game, Distributed algorithm.**

I. Introduction

NOWADAYS, with the surging of mobile Internet traffic, the traditional radio access networks (RANs) are facing new challenges [1]. Among them, an intimidating one is caused by the dedicated association of the baseband unit (BBU) and the remote radio head (RRH). Specifically, in a RAN, each base station (BS) consists of a BBU for baseband signal processing and a RRH for transmitting/receiving radio signals. However, a rigid arrangement can seriously limit the power efficiency and adaptivity of the RAN. For instance, when the RAN scales up with more BSs deployed, it has to face the energy consumption increase from both the BBU and RRH as they need exclusive cooling systems. Moreover, as different BSs' RRHs cannot access the BBU's processing capacity of one another, a BBU can be either saturated or under-utilized from time to time, depending on the dynamic traffic fluctuation.

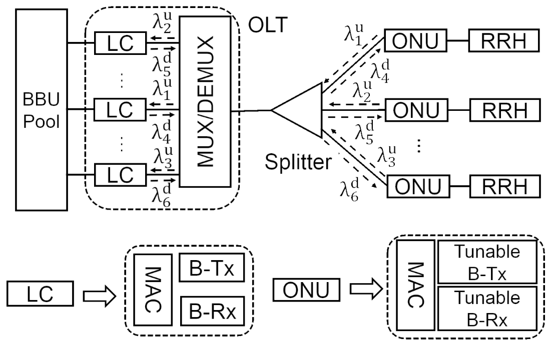

Fig. 1. Architecture of TWDM-PON-based C-RAN.

To address these issues, cloud RAN (C-RAN) has been proposed and considered as a promising solution [1–4]. Basically, C-RAN moves BBUs to a cloud-based BBU pool while leaves RRHs in the cell sites of BS'. By doing so, the static and dedicated mapping among BBUs and RRHs would be broken up, and thus a virtual BS (vBS), which uses the process capacity allocated from the BBU pool, can be dynamically formed to handle the signals from/to a particular RRH. Hence, system scalability and elasticity can be greatly improved. Note that, even though C-RAN is beneficial in terms of cost, scalability and flexibility, there are still some technical issues that should be addressed before it can be widely deployed. Most importantly, since the BBU pool and the RRHs in cell sites are in different locations, we have to transmit large amounts of baseband sampling data with very low latency. Although the existing wired access network technologies, such as digital subscriber line (DSL) [5] and hybrid fiber-coaxial (HFC) [6, 7] can be directly leveraged, their bandwidth capacity might be insufficient. Fortunately, the abundant bandwidth capacity of time-and-wavelength-division-multiplexing based passive optical networks (TWDM-PONs) makes them promising candidates for realizing ultra-low latency data transmissions in C-RAN [8].

Fig. 1 shows the architecture of a TWDM-PON-based C-RAN. On the optical line terminal (OLT) side, the cloud-based BBU pool connects to the line-card (LC) array, which uses LCs operating at different wavelength channels to communicate with the optical network units (ONUs) that are attached to the RRHs. Here, each LC consists of a pair of burst-mode transmitter/receiver (B-Tx/B-Rx) [9] and a media access control (MAC) module. In the downstream direction (*i.e.*, LCs

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Manuscript received November 23, 2016.

to ONUs), the optical signals from the LCs are combined by the wavelength-division multiplexer (MUX), transmitted on the fiber link, and then delivered to the ONUs by the optical splitter. On the other hand, the upstream signals from the ONUs are merged before the fiber transmission and then directed to the LCs by the wavelength-division de-multiplexer (DEMUX) according to their wavelength channels. To support this, the ONU that locally connects to the RRH in each cell site includes a pair of tunable B-Tx/B-Rx and a MAC module.

Note that, since each LC operates on a pair of dedicated downstream/upstream wavelength channels, the network system that consists of the LC and all the ONUs using its wavelength channel actually works as an independent TDM-PON. Meanwhile, if we assume that the ONUs are colorless and can register to different LCs at will, the concept of virtual TDM-PON (vTDM-PON) [10] emerges, which means that a vBS can be formulated with it dynamically to adapt to various traffic demands from the RRHs. Specifically, each vTDM-PON is identified by a LC that can be accessed by the BBU pool and operates on a pair of dedicated downstream/upstream wavelength channels, and includes several ONUs each of which hosts a RRH. The communications between the LC and its ONUs share the same downstream/upstream wavelength channels in a TDM manner. Previously, people have studied how to instantiate vBS adaptively in the TWDM-PON-based C-RAN by formulating vTDM-PONs and allocating processing capacity in the BBU pool with the considerations of traffic consolidation and energy saving [11, 12]. Note that, these studies relied on centralized algorithms for vTDM-PON formation. Although the centralized algorithms could be effective, putting the whole decision-making in the central office might increase the complexity of problem solving and induce unnecessary network control and management (NC&M) overheads. On the other hand, distributed algorithms might be more scalable and failure-proof [13, 14].

In this paper, we address the problem of forming vTDM-PONs adaptively in a TWDM-PON-based C-RAN with a distributed mechanism. Specifically, we consider the scenario in which the ONU of each RRH has the initiative to choose a proper LC (*i.e.*, a vTDM-PON) to register to based on its knowledge on the C-RAN, *i.e.*, the bandwidth demands of all the ONUs. It is known that game theory is a powerful mathematical tool for distributed optimization [15], and it has already been leveraged to solve the optimization problems in various networks [16–18]. Therefore, we first consider the static case where the traffic loads of the RRHs are known, formulate a vTDM-PON formation game model, transform the game into a potential game by designing a proper potential function for it, and prove the existence of Nash equilibrium (NE) points in the game. Then, we propose a distributed algorithm that can converge to an NE point quickly to let each ONU choose its vTDM-PON intelligently. Meanwhile, we also formulate a mixed integer linear programming (MILP) model as the centralized benchmark to solve the problem exactly. Next, we extend our work to consider the dynamic case in which the traffic loads of the RRHs can change on-the-fly, and extend the distributed algorithm to allow each ONU to adjust its vTDM-PON registration adaptively, while considering the tradeoff between network performance and ONU migration cost. We also prove the existence of NE point(s) in this dynamic game. Finally, we evaluate the proposed algorithms with extensive simulations and verify their effectiveness.

The rest of the paper is organized as follows. In Section II, we discuss the static case of vTDM-PON formation and propose a distributed vTDM-PON registration algorithm for it. Section III formulates a centralized MILP model as the benchmark. The dynamic vTDM-PON formation is studied in Section IV and the performance evaluation is presented in Section V. Finally, Section VI summarizes the paper.

II. Static vTDM-PON Formation

A. Network Model

In the C-RAN, we denote the available vTDM-PONs by $L = \{1, 2, ..., m\}$, each of which corresponds to a LC operating on a pair of dedicated downstream/upstream wavelength channels. On the LC side, the traffic processing rate of each vTDM-PON is assumed to be identical as μ. While on the ONU side, we denote the set of cell sites (or ONUs) by $C = \{1, 2, ..., n\}$, and their traffic loads are $\Lambda = \{\lambda_1, \lambda_2, ..., \lambda_n\}$ correspondingly. Then, as the ONU of a RRH can choose to register to an arbitrary vTDM-PON based on its knowledge on the C-RAN, we model the registration process as a noncooperative game among the ONUs. Specifically, in the game, each ONU $i \in C$ is a player, and its strategy profile is $S_i = L = \{1, 2, \cdots, m\}$, which means that the ONU can register to any available vTDM-PON. Therefore, for all the ONUs (*i.e.*, players), their overall strategy profile is $\mathbf{S} = S_1 \times ... \times S_i ... \times S_n$. Meanwhile, for each game, we denote the strategy that ONU i selects (*i.e.*, registering to a specific vTDM-PON) as s_i, which can be an arbitrary element in S_i (*i.e.*, $s_i \in S_i$).

In the noncooperative game, each ONU $i \in C$ tries to maximize its payoff, which consists of two parts, *i.e.*, the utility and the price.

Definition 1. *The **utility function** of an ONU i is defined as*

$$U_i(\vec{s}) = \alpha \cdot \left[\mu - \sum_{j=1}^{n} I(s_j, s_i) \cdot \lambda_j\right], \tag{1}$$

where the vector $\vec{s} = \langle s_1, ..., s_i, ..., s_n \rangle \in \mathbf{S}$ represents a set of specified vTDM-PON registration strategies of all the ONUs, α is a positive weight coefficient, s_i is the registration strategy of ONU i, and $I(s_j, s_i)$ is the flag to indicate whether two ONUs i and j register to the same vTDM-PON, i.e.,

$$I(s_j, s_i) = \begin{cases} 1, & s_j = s_i, \\ 0, & s_j \neq s_i. \end{cases} \tag{2}$$

Note that, the utility in Eq. (1) is inversely proportional to the average traffic processing delay of ONU i, which is

$$\overline{D_i} = \frac{1}{\mu - \sum\limits_{j=1}^{n} I(s_j, s_i) \cdot \lambda_j}, \tag{3}$$

if ONU i decides to register to vTDM-PON s_i.

Definition 2. *The* ***price function*** *of an ONU i is defined as*

$$P_i(\vec{s}) = f(s_i), \tag{4}$$

where $f(\cdot)$ is a non-decreasing and positive function of vTDM-PON's ID s_i. With this price function, we can encourage the ONUs to use the first-fit scheme for vTDM-PON registration and thus vTDM-PON utilization can be consolidated for reducing energy consumption.

Therefore, the payoff function of ONU i is

$$\begin{aligned}\Phi_i(\vec{s}) &= U_i(\vec{s}) - P_i(\vec{s}) \\ &= \alpha \cdot \left[\mu - \sum_{j=1}^{n} I(s_j, s_i)\cdot\lambda_j\right] - f(s_i).\end{aligned} \tag{5}$$

B. Nash Equilibrium

In the aforementioned noncooperative game, the ONUs make their vTDM-PON registration decisions in a distributed and independent way, which means that each ONU selects the vTDM-PON to register independently and submits their registration requests simultaneously[1]. Hence, to design the distributed vTDM-PON registration algorithm, we need to find the ONUs' best-responses to each other's strategies, which can be done by leveraging the concept of Nash equilibrium (NE) [15]. Specifically, the NE of a noncooperative game is the strategy profile of all the players in which none of the players can increase their payoffs by changing the strategy unilaterally [15]. Therefore, if we can prove the existence of NE point(s) in the game and develop a method to find at least one NE point, the distributed vTDM-PON registration algorithm can be obtained. In the following, we prove the existence of NE point(s) in the game by transforming it into a weighted potential game [19–22].

Definition 3. *A game $G = \langle C, \{S_i : i \in C\}, \{\Phi_i : i \in C\}\rangle$ is a* ***weighted potential game****, if there exists a potential function $PF(\cdot)$ such that for any $i \in C$ and any $\langle s_i, s_{-i}\rangle \in \mathbf{S}$ and $\langle s_i^*, s_{-i}\rangle \in \mathbf{S}$, we have [19]*

$$\begin{aligned}\Phi_i(\langle s_i^*, s_{-i}\rangle) &- \Phi_i(\langle s_i, s_{-i}\rangle) \\ &= \omega_i \cdot \left[PF(\langle s_i^*, s_{-i}\rangle) - PF(\langle s_i, s_{-i}\rangle)\right],\end{aligned} \tag{6}$$

where we use s_{-i} to represent the strategies of other players except for player i, $s_i^* \in S_i$ is a strategy that is different from s_i, and ω_i is the weight coefficient.

Theorem 1. *The game of static vTDM-PON formation is a finite weighted potential game.*

[1]Note that, even though the ONUs operate in a distributed manner, each ONU requires some information about the other ONUs (*i.e.*, their strategy profiles) to calculate its payoff, according to Eq. (5). Therefore, we assume that each ONU sends its information to the OLT periodically, then the OLT shares the information with all the other ONUs, and all of these are done before the game at each service time.

Proof: Firstly, we define the function $PF(\cdot)$ as

$$\begin{aligned}PF(\vec{s}) &= -\sum_{j=1}^{n}\sum_{k=1}^{n}\frac{\alpha}{2}\cdot\lambda_j\cdot\lambda_k\cdot I(s_j,s_k) - \sum_{j=1}^{n}\lambda_j\cdot f(s_j) \\ &= -\frac{\alpha}{2}\cdot\left[\sum_{j\neq i}\sum_{k\neq i}\lambda_j\cdot\lambda_k\cdot I(s_j,s_k) + \lambda_i^2\right] - \sum_{j\neq i}\lambda_j\cdot f(s_j) \\ &\quad - \alpha\cdot\sum_{j\neq i}\lambda_j\cdot\lambda_i\cdot I(s_j,s_i) - \lambda_i\cdot f(s_i).\end{aligned} \tag{7}$$

Then, we have

$$\begin{aligned}&PF(\langle s_i^*, s_{-i}\rangle) - PF(\langle s_i, s_{-i}\rangle) \\ &= \lambda_i\cdot\Bigg(\left\{\alpha\cdot\left[\mu - \sum_{j=1}^{n}\lambda_j\cdot I(s_j,s_i^*)\right] - f(s_i^*)\right\} \\ &\quad - \left\{\alpha\cdot\left[\mu - \sum_{j=1}^{n}\lambda_j\cdot I(s_j,s_i)\right] - f(s_i)\right\}\Bigg) \\ &= \lambda_i\cdot\left[\Phi_i(\langle s_i^*, s_{-i}\rangle) - \Phi_i(\langle s_i, s_{-i}\rangle)\right].\end{aligned} \tag{8}$$

Finally, we get

$$\begin{aligned}&\Phi_i(\langle s_i^*, s_{-i}\rangle) - \Phi_i(\langle s_i, s_{-i}\rangle) \\ &\qquad = \frac{1}{\lambda_i}\cdot\left[PF(\langle s_i^*, s_{-i}\rangle) - PF(\langle s_i, s_{-i}\rangle)\right].\end{aligned} \tag{9}$$

Hence, we prove that the game of static vTDM-PON formation is a weighted potential game with the potential function in Eq. (7). Moreover, since the game has finite strategy profiles (*i.e.*, $|\mathbf{S}| = m^n$), it should have at least one NE point [19]. ■

C. Distributed vTDM-PON Registration Algorithm

Based on the theory of best-response dynamics [23], we propose an algorithm to determine the NE-based vTDM-PON registration strategies for all the ONUs, as shown in *Algorithm* 1. Note that, since the inputs of *Algorithm* 1, which are L, μ, C, $\Lambda=\{\lambda_1, \lambda_2, ..., \lambda_n\}$, and α, can be known to all the ONUs as the C-RAN's status, each ONU can use *Algorithm* 1 to determine its own vTDM-PON registration strategy in a distributed and independent manner. *Lines* 1-2 are for the initialization, during which we randomly select a set of vTDM-PON registration strategies for all the ONUs (*i.e.*, $\vec{s}_0$) and use it as the initial strategy set. The while-loop that covers *Lines* 3-14 tries to find the NE-based vTDM-PON registration strategy set $\vec{s}_*$ by iteration. Specifically, the for-loop covering *Lines* 4-7 checks each ONU and updates the registration strategy set according to the equation in *Line* 6, where s_{k-1}^{-i} represents the strategies of other ONUs except for ONU i in the $(k-1)$-th for-iteration. Then, *Lines* 8-13 determine whether to stop the while-loop and output $\vec{s}_*$. Basically, if the obtained registration strategy set does not change anymore (*i.e.*, $\vec{s}_k = \vec{s}_t$), we can conclude that an NE point $\vec{s}_*$ has been found.

Theorem 2. Algorithm *1 can converge to an NE point within finite iterations.*

Proof: Eq. (9) suggests that if $\Phi_i(\langle s_i^*, s_{-i}\rangle) \geq \Phi_i(\langle s_i, s_{-i}\rangle)$, then $PF(\langle s_i^*, s_{-i}\rangle) \geq PF(\langle s_i, s_{-i}\rangle)$, which is because $\lambda_i > 0$. Hence, we can find such an improvement path $\Gamma = \vec{s}_0 \rightarrow \vec{s}_1 \cdots \rightarrow \vec{s}_k \cdots$, $\vec{s}_k \in \mathbf{S}$, which satisfies the following condition: for every $k \geq 1$, there exist

Algorithm 1: Determining NE-based vTDM-PON Registration Strategies for ONUs

Input: L, μ, C, Λ=$\{\lambda_1, \lambda_2, ..., \lambda_n\}$, α
Output: NE-based registration strategy set $\vec{s}_*$

select a registration strategy set $\vec{s}_0 \in \mathbf{S}$ randomly;
$k = 0$, $\vec{s}_t = \vec{s}_0$;
while $k < +\infty$ **do**
  for *each ONU* $i \in C$ **do**
    $k = k + 1$;
    $\vec{s}_k = \langle \underset{s_i \in L}{\text{argmax}} \left[\Phi_i \left(\langle s_i, s_{k-1}^{-i} \rangle \right) \right], s_{k-1}^{-i} \rangle$;
  end
  if $\vec{s}_k = \vec{s}_t$ **then**
    $\vec{s}_* = \vec{s}_k$;
    break;
  else
    $\vec{s}_t = \vec{s}_k$;
  end
end

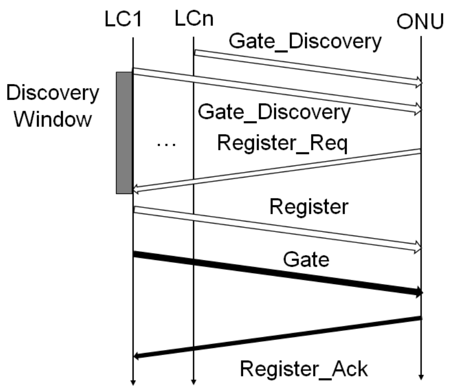


Fig. 2. Procedure of distributed vTDM-PON registration for ONUs.

$\vec{s}_k = \langle s_i^*, s_{k-1}^{-i} \rangle$ and $\vec{s}_{k-1} = \langle s_i, s_{k-1}^{-i} \rangle$, such that we have $\Phi_i \left(\vec{s}_k \right) \geq \Phi_i \left(\vec{s}_{k-1} \right), \ \forall i \in C, \ \{s_i, s_i^* : s_i^* \neq s_i, \ s_i, s_i^* \in S_i\}$. Consequently, the value of function $PF(\cdot)$ will increase along the improvement path Γ. As the game only has finite strategy profiles, the length of every improvement path must be finite. Moreover, when the improvement path reaches a maximal point of function $PF(\cdot)$, none of the ONUs can increase the value of function $PF(\cdot)$ by changing the strategy unilaterally. This indicates that the improvement path has converged to an NE point of the game, which proves that *Algorithm* 1 can converge to an NE point within finite iterations. ∎

D. Distributed vTDM-PON Registration Procedure

We also consider the procedure to realize the distributed vTDM-PON registration for the ONUs. Fig. 2 shows the flowchart of the message exchanges for it. Basically, the OLT periodically broadcasts *Gate_Discovery* messages to all the ONUs via the downstream wavelength channels. This message encodes the start- and end-time of a discovery window, during which the offline ONUs can register, and the network status that is necessary for the ONUs to figure out their target vTDM-PONs. An unregistered ONU first randomly selects a downstream wavelength channel to listen, and once it receives a *Gate_Discovery* message, it determines its target vTDM-PON with *Algorithm* 1 and then tunes its downstream/upstream wavelength channels to the target vTDM-PON. Next, the ONU transmits a *Register_Req* message to the OLT, which encodes the information of its target vTDM-PON. After receiving the *Register_Req* message, the OLT allocates a logical link identifier (LLID) to the ONU by replying a *Register* message. Soon after this, the OLT sends a *Gate* message to the ONU. As the reply, the ONU sends a *Register_Ack* message to the OLT, which completes its vTDM-PON registration process.

III. Centralized MILP Benchmark

In this section, we formulate a mixed integer linear programming (MILP) model to solve the problem of vTDM-PON formation exactly and use it as the centralized benchmark.

Parameters:

- L: the set of available vTDM-PONs.
- μ: the traffic processing rate of each vTDM-PON.
- C: the set of ONUs.
- Λ: the set of traffic loads of the ONUs.
- m: the number of available vTDM-PONs.
- n: the number of ONUs.
- α: a positive coefficient.

Variables:

- s_i: the integer variable that indicates the registration strategy of ONU i (*i.e.*, the ID of its target vTDM-PON) and thus $s_i \in [0, m]$.
- $I_{i,j}$: the boolean variable that equals 1 if $s_i = s_j$, and 0 otherwise.
- $x_{i,j}$: the boolean variable that equals 1 if $s_i \geq s_j$, and 0 otherwise.
- Φ_i: the real variable that indicates the payoff of ONU i.

Note that, the variable $I_{i,j}$ is introduced to represent whether ONUs i and j choose to register to the same vTDM-PON or not. However, the relation among $I_{i,j}$, s_i and s_j is not linear, and thus we introduce another variable $x_{i,j}$ to help transform the nonlinear constraints to linear ones.

Objectives:

The optimization objective is to maximize the total payoff of all the ONUs.

$$Maximize \quad \sum_{i \in C} \Phi_i \tag{10}$$

Constraints:

$$\begin{cases} x_{i,j} \geq \dfrac{s_i - s_j + 1}{m}, \\ x_{i,j} \leq \dfrac{s_i - s_j + m}{m}, \end{cases} \quad \forall i, j \in C. \tag{11}$$

Eq. (11) determines the value of $x_{i,j}$.

$$I_{i,j} = x_{i,j} + x_{j,i} - 1, \quad \forall i, j. \tag{12}$$

Eq. (12) determines the value of $I_{i,j}$.

$$\Phi_i = \alpha \cdot \left[\mu - \sum_{j \in C} I(i,j) \cdot \lambda_j \right] - f(s_i), \quad \forall i. \tag{13}$$

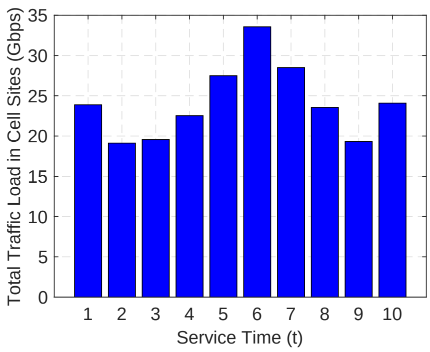


Fig. 3. Example of traffic load fluctuation over time in cell sites.

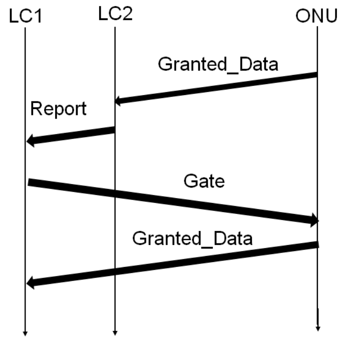


Fig. 4. Procedure of ONU migration.

Eq. (13) calculates the payoff of each ONU. Note that, we use a linear price function $f(s_i)$ to ensure the model's linearity.

IV. Dynamic vTDM-PON Formation

A. Distributed vTDM-PON Registration Algorithm

Note that, the static vTDM-PON formation discussed above oversimplifies the network operation in a C-RAN. In a practical C-RAN, the network status changes dynamically over time. For instance, Fig. 3 plots a typical fluctuation trend of the total traffic load in a mobile network's cell sites (the duration of each service time t is an hour) [1]. Hence, the "once for all" vTDM-PON registration scheme developed for a static C-RAN needs to be extended to consider dynamic vTDM-PON formation. Specifically, to adapt to traffic fluctuations, we need to allow each ONU to adjust its target vTDM-PON dynamically through ONU migration [24]. Specifically, an ONU might change its vTDM-PON from a heavy-loaded one to a relatively empty one to avoid abnormally long traffic processing delay, or, when the overall traffic load becomes lighter, it might switch to a vTDM-PON whose ID is lower for consolidating the usage of vTDM-PONs and saving energy. Nevertheless, it is known that ONU migration might introduce additional processing delay due to vTDM-PON de-/re-registrations, and it requires buffering data traffic of RRH during the downtime for service migration, which could lead to data losses due to the limited buffer length [24, 25]. Hence, we have to consider the overheads of ONU migration.

Based on these considerations, we design a game for dynamic vTDM-PON formation. Basically, at a service time t, the traffic loads of the ONUs are $\Lambda^t = \{\lambda_1^t, \lambda_2^t, ..., \lambda_n^t\}$, and we use $(\vec{s})^t = \langle s_1^t, ..., s_i^t, ..., s_n^t \rangle \in \mathbf{S}$ to denote a set of specified vTDM-PON registration strategies of all the ONUs. Here, the registration strategy of ONU i at t can be different from that at $t-1$ (*i.e.*, $s_i^t \neq s_i^{t-1}$), which means that an ONU migration has been performed. In order to consider the overheads of ONU migration, we redefine the price function of each ONU i as

$$P_i'\left((\vec{s})^t\right) = f\left(s_i^t\right) + \beta \cdot I'(s_i^t, s_i^{t-1}) \cdot \lambda_i^t, \tag{14}$$

where function $f(\cdot)$ is the same as that in Eq. (4) and the second term quantifies the cost of an ONU migration. Here, for simplicity, we assume that the cost of an ONU migration is linearly related to the amount of traffic that needs to be migrated, and thus β is the positive coefficient to weight the traffic amount and $I'(s_i^t, s_i^{t-1})$ is the flag function to indicate whether an ONU migration has been performed for ONU i from $t-1$ to t,

$$I'\left(s_i^t, s_i^{t-1}\right) = \begin{cases} 1, & s_i^t \neq s_i^{t-1}, \\ 0, & s_i^t = s_i^{t-1}. \end{cases} \tag{15}$$

Therefore, the payoff function becomes

$$\begin{aligned} \Phi_i'\left((\vec{s})^t\right) &= U_i\left((\vec{s})^t\right) - P_i'\left((\vec{s})^t\right) \\ &= \alpha \cdot \left(\mu - \sum_{j=1}^{n} I\left(s_j^t, s_i^t\right) \cdot \lambda_j^t\right) - f\left(s_i^t\right) \\ &\quad - \beta \cdot I'(s_i^t, s_i^{t-1}) \cdot \lambda_i^t. \end{aligned} \tag{16}$$

Here, if we define $f'\left(s_i^t\right) = f\left(s_i^t\right) + \beta \cdot I'(s_i^t, s_i^{t-1})$, Eq. (16) would be transformed into a similar expression as Eq. (5). This suggests that *Theorem* 1 is still valid, which is because the proof of the existence of NE point(s) in Section II-B can be adapted by simply replacing $f(s_i)$ with $f'\left(s_i^t\right)$. Hence, the game of dynamic vTDM-PON formation is still a finite weighted potential game, which means that there exists at least one NE point for the game at each service time t. Consequently, we can still use *Algorithm* 1 to determine the NE-based vTDM-PON registration strategies for the ONUs in this dynamic case. In other words, at each service time t, each ONU decides whether to change its vTDM-PON based on the NE point(s) derived using the payoff function in Eq. (16).

B. ONU Migration Procedure

Fig. 4 shows the flowchart of message exchanges for an ONU migration. Basically, if an ONU wants to change its vTDM-PON registration, it encodes the deregistration request and information on the new vTDM-PON in a *Granted_Data* message to its current vTDM-PON. After receiving a deregistration request from an ONU, a vTDM-PON sends a *Report* message to the new vTDM-PON to hand the ONU's registration request over and then stops sending *Gate* messages to the ONU that is about to leave. When the registration process is done, the new vTDM-PON sends a *Gate* message to the ONU, and then the ONU starts to transmit data to the new vTDM-PON via the *Granted_Data* messages.

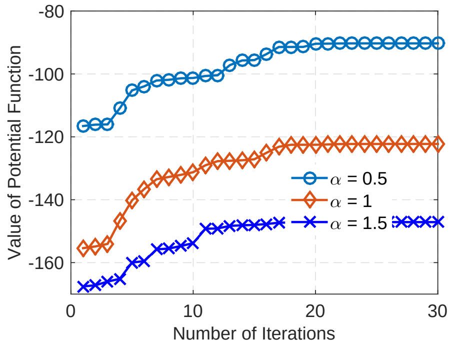


Fig. 5. Convergence performance of the proposed distributed algorithm.

V. Performance Evaluation

In this section, we present the simulation results for performance evaluation. The simulations use Matlab R2015a running on a personal computer with 3.10 GHz Inter Core i3 CPU and 8 GB RAM, while the MILP model is solved with the GNU linear programming kit (GLPK) [26].

A. Static Case of vTDM-PON Formation

1) Convergence Performance: We first consider a C-RAN with 8 available vTDM-PONs and 32 cell sites (or ONUs), *i.e.*, $m = 8$ and $n = 32$. The traffic processing rate of each vTDM-PON is assumed to be $\mu = 10$ Gbps, while the traffic load in each cell site λ_i is uniformly distributed within $[0, 1.5]$ Gbps. For simplicity, the price function in Eq. (4) uses the expression $f(s_i) = s_i$. Fig. 5 shows the convergence performance of the proposed distributed vTDM-PON registration algorithm, where we test the algorithm for $\alpha \in \{0.5, 1, 1.5\}$. Here, we plot the value of the potential function $PF(\cdot)$ defined in Eq. (7) versus the number of iterations, since according to *Theorem* 2, the convergence of $PF(\cdot)$ is equivalent to the convergence of *Algorithm* 1. It can be seen clearly that the proposed algorithm can converge to an NE point with only a few iterations (*i.e.*, 26 iterations at most in Fig. 5). Moreover, it is interesting to notice that even though the value of α can affect the final result of the potential function $PF(\cdot)$, it has low influence on converging speed of the proposed algorithm.

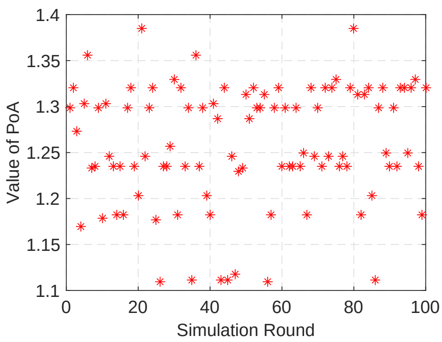
2) Price of Anarchy (PoA): We define "price of anarchy" (PoA) as the performance metric to evaluate the quality of the NE point obtained by our proposed algorithm.

Definition 4. *For all the ONUs in the game, the* ***price of anarchy*** *(PoA) of a NE point is the ratio between the optimum total payoff obtained by the MILP model in Section III and the total payoff at the NE point.*

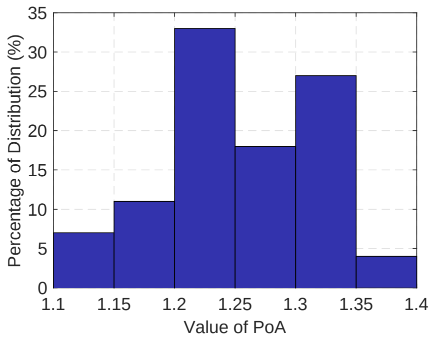
Note that the centralized MILP model formulated in Section III can provide the optimum solution to maximize the total payoff of all the ONUs. Hence, we can use PoA to quantify the performance loss due to the distributed algorithm in terms of total payoff. We run 100 independent simulations with $m = 8$, $n = 8$ and $\alpha = 1$ to analyze our proposed algorithm's performance on PoA, and Fig. 6 illustrates the results. Here, the ONUs' traffic loads are randomly selected within $[0, 7]$ Gbps. The values of PoA are plotted in Fig. 6(a), which indicate that PoA takes several discrete values, each of which corresponds to an NE point in the static vTDM-PON formation game. According to Eq. (13), the ONUs that register to a same vTDM-PON have the same payoff value. If we regard the price value of one ONU registered on a vTDM-PON as dummy traffic, the ONU's payoff value would be the difference between the processing rate μ and its total traffic load, which includes both the actual total traffic from all the ONUs on the vTDM-PON and its dummy traffic. At an NE point, none of the ONUs can increase its payoff value by changing its strategy unilaterally. Thus, an NE point is actually equivalent to the situation in which each active vTDM-PON holds almost the same amount of total traffic from its ONUs, including the dummy traffic. Since there are multiple such load-balanced situations for the vTDM-PONs, the NE points are not unique in the game. Moreover, since the values of PoA are close to 1, *i.e.*, ranging within $[1.1, 1.4]$, the effectiveness of our proposed distributed algorithm gets confirmed. Fig. 6(b) shows the distribution of the values of PoA, and we observe that more than 78% of the values are located within $[1.2, 1.35]$. This suggests that the proposed algorithm has relatively good stability to find an NE point whose quality is medium.

Table I compares the centralized MILP benchmark and the proposed distributed algorithm in terms of average running time. Here, we test different combinations of the number of available vTDM-PONs m and the number of ONUs n. As expected, the running time of the centralized MILP increases much more dramatically than that of our proposed distributed algorithm. For example, the running time of the centralized MILP becomes around 2300 times longer when the combination of $\{m, n\}$ changes from $\{6, 6\}$ to $\{8, 8\}$, while for the same parameter change, the running time of our proposed distributed algorithm only increases for about 1.4 times. More specifically, due to the constraints in Eqs. (11)-(12), the complexity of the centralized MILP depends heavily on the number of ONUs n. When n increases to 16 or more, the centralized MILP can no longer obtain the optimum solution within 24 hours. In contrast, our proposed algorithm can finish the computation within 46 msec for all the combinations of $\{m, n\}$ in Table I. These results verify the rationality of considering the distributed approach for vTDM-PON formation in this work. Furthermore, in the simulations, the average PoA from our proposed distributed algorithm is always kept below 1.2590.

3) Effects of Coefficient α: We then change the value of α within $[0.5, 2]$ to investigate its effects 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 ONU). We assume that there are 8 available vTDM-PONs and 32 ONUs, *i.e.*, $m = 8$ and $n = 32$, and the average traffic load from each ONU is 1 Gbps. Fig. 7 shows the simulation results, and it can be seen that the average delay in vTDM-PONs decreases with α. This is because, according to Eq. (5), a smaller α pushes the cost for the ONUs to register to an empty vTDM-PON higher, and hence they tend to share vTDM-PON(s), which makes the average



(a) PoA in simulations



(b) Distribution of PoA

Fig. 6. Results on price of anarchy (PoA) of the proposed algorithm.

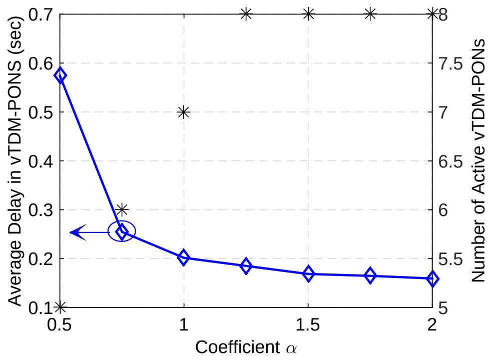


Fig. 7. Effects of α on average delay and number of active vTDM-PONs.

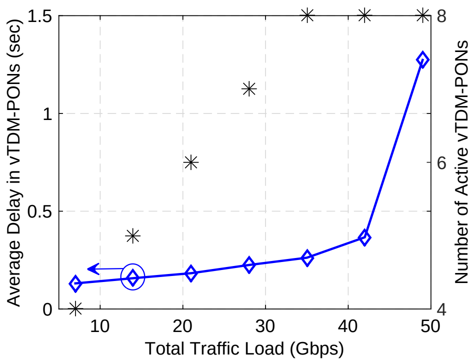


Fig. 8. Effects of total traffic load on average delay and number of active vTDM-PONs.

TABLE I
COMPARISON BETWEEN CENTRALIZED MILP BENCHMARK AND PROPOSED DISTRIBUTED ALGORITHM.

m	n	Average Running Time (Seconds)		Average PoA
		Centralized MILP	Distributed Algorithm	
6	6	0.2000	0.0068	1.1801
6	16	-	0.0331	-
7	7	1.1000	0.0087	1.2304
7	16	-	0.0359	-
8	8	471.4000	0.0097	1.2590
8	16	-	0.0454	-

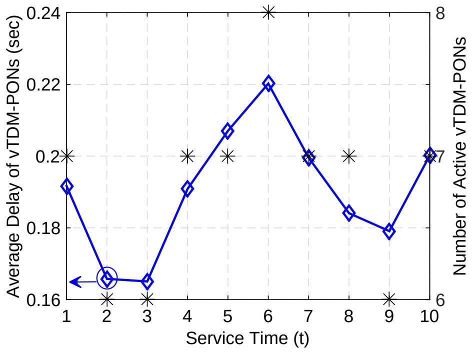
delay in vTDM-PONs longer. For the same reason, the number of active vTDM-PONs increases with α. These results verify the effectiveness of α on balancing the tradeoff between the average delay in vTDM-PONs and the number of active vTDM-PONs. Note that, due to the restriction from μ, the value of α should be carefully chosen to avoid causing traffic congestions in the vTDM-PONs.

4) Effects of Total Traffic Load: We change the total traffic load from all the ONUs from 0 to 50 Gbps and keep $m = 8$, $n = 32$ and $\alpha = 1$. Fig. 8 shows the effects of the total traffic load on the average traffic processing delay of the vTDM-PONs and on the number of active vTDM-PONs. As expected, both the average delay and number of active vTDM-PONs increase with the total traffic load. Basically, due to the utility function defined in Eq. (1), when the traffic load increases, the ONUs tend to register to empty vTDM-PONs for reducing the average traffic processing delay in their target vTDM-PONs.

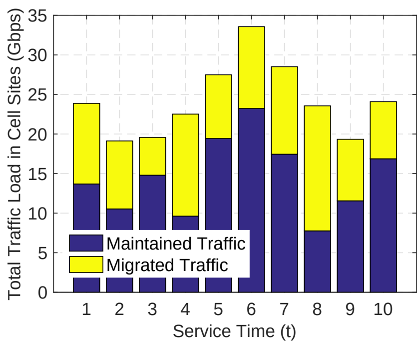
B. Dynamic Case of vTDM-PON formation

We generate dynamic traffic loads for the ONUs as plotted in Fig. 3, and simulate two scenarios for the dynamic vTDM-PON formation: 1) ignoring the ONU migration cost (*i.e.*, setting $\beta = 0$ in Eq. (16)), and 2) taking the ONU migration cost into account. The dynamic traffic in Fig. 3 is randomly generated with sine function to emulate the fluctuation, and we use it to test whether our proposed algorithm can improve network capacity adaptivity in case of highly dynamic traffic. In the simulations, *Algorithm* 1 is executed at every service time. Note that, to adapt to the dynamic operation, *Line* 1 of *Algorithm* 1 is modified such that the initial strategy profile at the current service time is the selected strategy profile at the previous service time.

Fig. 9 shows the results of the dynamic vTDM-PON formation that does not consider the ONU migration cost. It is promising to see that our proposed distributed algorithm makes the number of active vTDM-PONs change adaptively according to the traffic load fluctuation. Specifically, when the total traffic load is relatively low, the ONUs try to avoid registering to empty vTDM-PONs for energy saving, *e.g.*, the cases at service time $t = \{2, 3, 9\}$ in Fig. 9(a). On the other hand, when the total traffic load becomes relatively high, the ONUs tend to select empty vTDM-PONs for reducing their traffic processing delay, *e.g.*, the cases at service time $t = \{4, 6, 10\}$. Meanwhile, in Fig. 9(b), we can see that at certain service time, *i.e.*, $t = \{4, 8\}$, the amount of migrated

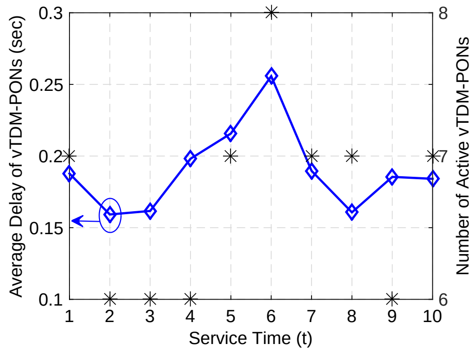


(a) Average delay and number of active vTDM-PONs.

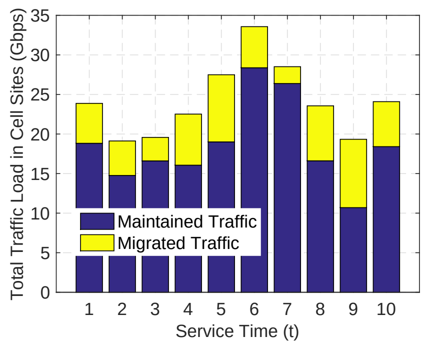


(b) Maintained and migrated traffic.

Fig. 9. Results on dynamic vTDM-PON formation ($\beta = 0$).



(a) Average delay and number of active vTDM-PONs.



(b) Maintained and migrated traffic.

Fig. 10. Results on dynamic vTDM-PON formation ($\beta > 0$).

traffic is higher than that of maintained traffic (*i.e.*, traffic from the ONUs that have not changed their vTDM-PONs). This is because we overlook the ONU migration cost and thus the ONUs just try to change their vTDM-PON registrations at will for reduced traffic processing delay.

Fig. 10 shows the results of the dynamic vTDM-PON formation that takes the ONU migration cost into consideration. As expected, the ONUs tend to maintain their vTDM-PON registrations unchanged this time. Hence, the average traffic processing delay in Fig. 10(a) becomes higher than that in Fig. 9(a), while the number of active vTDM-PONs in Fig. 10(a) is less than that in Fig. 9(a). Moreover, by comparing the results in Fig. 9(b) and Fig. 10(b), we find that the amount of migrated traffic has been reduced significantly when we consider the ONU migration cost. This verifies the effectiveness of β on reducing unnecessary ONU migrations.

VI. Conclusion

This paper studied a game-theoretic approach to realize distributed vTDM-PON registration in TWDM-PON-based C-RANs. We first considered the static case in which the traffic load of each cell site is known, formulated a vTDM-PON formation game model, transformed the game into a weighted potential game to prove the existence of NE points, and proposed a distributed algorithm that can converge to an NE point to enable each ONU to choose its vTDM-PON intelligently. Then, we extended our work to address the dynamic case in which the traffic loads of the ONUs can change on-the-fly. We modified the distributed algorithm to allow each ONU to adjust its vTDM-PON registration adaptively, considering the tradeoff between network performance and ONU migration cost. Simulation results verified that the game models were well designed to provide relatively low PoA values, and the proposed distributed algorithms could converge to an NE point quickly and reduce the amount of migrated traffic significantly in dynamic vTDM-PON formation.

Acknowledgments

This work was supported in part by the NSFC Project 61371117, NSR Project for Universities in Anhui (KJ2014ZD38), the SPR Program of the CAS (XDA06011202), the Key Project of the CAS (QYZDY-SSW-JSC003), and the NGBWMCN Key Project under Grant No. 2017ZX03001019-004.

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