

Proofs for Two Properties in Online Resource Allocation

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Property 1. *The K types of resources are allocated sequentially, i.e., $r_{k'}(t) = B_{k'}, \forall k' < k$ is a necessary condition for $r_k(t) > 0$.*

Proof. The KKT conditions are given as:

$$Ma_k(t)h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) + Q_k(t) + \tau_k - v_k = 0, \quad (1)$$

$$v_k r_k(t) = 0, \quad (2)$$

$$\tau_k [B_k - r_k(t)] = 0, \quad (3)$$

$$v_k \geq 0, \quad (4)$$

$$\tau_k \geq 0, \quad (5)$$

$$\forall k = 1, \dots, K, \quad (6)$$

Assume that the optimal resource allocation policy $\mathbf{r}(t)$ satisfies

$$-\frac{1}{p_{k+1}(t)} < M \cdot h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) \leq -\frac{1}{p_k(t)} \quad (7)$$

then for $k' = 1, 2, \dots, k-1$, $\tau_{k'}$ has to be positive to satisfy Eqs. [(1),(4),(5),(7)], then $r_{k'}$ must equal to $B_{k'}$ given Eq. (3). Meanwhile, for $k' = k+1, k+2, \dots, K$, $v_{k'}$ has to be positive to satisfy Eqs. [(1),(4),(5),(7)], then $r_{k'}$ must equal to zero given Eq. (2). \square

Property 2. *If $M \cdot h'(C(t) + \sum_{k'=1}^{k-1} a_{k'}(t)r_{k'}(t)) < -\frac{1}{p_k(t)}$ and $B_k > 0$, the k -th resource will be allocated, i.e., $r_k(t) > 0$. Moreover, if $0 < Q_k(t) \leq \frac{Ma_k(t)}{4}$, then $r_k(t)$ satisfies*

$$r_k(t) = \min \left\{ \frac{\gamma(t) - C(t) - \sum_{k'=0}^{k-1} a_{k'}(t)B_{k'}}{a_k(t)}, B_k \right\}, \quad (8)$$

where $\gamma(t) = \ln(-1 + \frac{Ma_k(t) + \sqrt{M^2 a_k(t)^2 - 4Ma_k(t)Q_k(t)}}{2Q_k(t)})$; if $Q_k(t) = 0$, we have $r_k(t) = B_k$.

Proof. If $M \cdot h'(C(t) + \sum_{k'=1}^{k-1} a_{k'}(t)r_{k'}(t)) < -\frac{1}{p_k(t)}$ and $B_k > 0$, then $r_k(t)$ has to be positive given Eqs. [(1),(2),(3),(4),(5)], otherwise τ_k will be zero and Eq. (1) is not satisfied.

Moreover, according to Eqs. [(2),(3),(4),(5)], when $0 <$

$r_k(t) < B_k$, i.e., $\tau_k = v_k = 0$, r_k satisfies

$$Q_k(t) + Ma_k(t)h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) = 0. \quad (9)$$

By calculating, we have

$$\begin{aligned} & h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) \\ &= \frac{-\exp(C(t) + \sum_{k'=0}^{k-1} a_{k'}(t)B_{k'} + a_k(t)r_k(t))}{\left(1 + \exp\left(C(t) + \sum_{k'=0}^{k-1} a_{k'}(t)B_{k'} + a_k(t)r_k(t)\right)\right)^2}. \end{aligned}$$

Let S denote $\exp\left(C(t) + \sum_{k'=0}^{k-1} a_{k'}(t)B_{k'} + a_k(t)r_k(t)\right)$. Then Eq. (9) becomes:

$$Q_k(t)s^2 + (2Q_k(t) - Ma_k(t))s + Q_k(t) = 0. \quad (10)$$

As a further step, we define the left side of the above equation as function $\beta(s)$. If $Q_k(t) > \frac{Ma_k(t)}{4}$, i.e., there is no solution to Eq. (10) and $Q_k(t) + Ma_k(t)h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) \geq 0$. Then the minimum of $Q_k(t)r_k(t) + M \cdot h(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t))$ appears at $r_k(t) = 0$. If $Q_k(t) \leq \frac{Ma_k(t)}{4}$, i.e., Eq. (10) has two solutions $s_1, s_2 = -1 + \frac{Ma_k(t)}{2Q_k(t)} \pm \frac{\sqrt{M^2 a_k(t)^2 - 4Ma_k(t)Q_k(t)}}{2Q_k(t)}$ (assuming $s_1 < s_2$). From s_1, s_2 , it can be easily get two $r_k(t)$ -s, which are denoted by $r_k^1(t)$ and $r_k^2(t)$ respectively. By calculating the gradient of $\beta(s)$, It can be observed that $r_k^1(t)$ is local maxima and $r_k^2(t)$ is local minima. Therefore, $r_k^2(t)$ is the optimal solution which ensures that the objective function $Q_k(t)r_k(t) + M \cdot h(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t))$ is the smallest when $Q_k(t) \leq \frac{Ma_k(t)}{4}$. When $Q_k(t) = 0$ and $r_k(t) > 0$, we have $v_k = 0$ given Eq. (2), and Eq. (1) can be simplified to $Ma_k(t)h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) + \tau_k = 0$, then $\tau_k = -Ma_k(t)h'(C(t) + \mathbf{a}(t)^\top \mathbf{r}(t)) \neq 0$. Therefore, according to Eq. (3), we have $r_k(t) = B_k$ when $Q_k(t) = 0$. \square