A Proportional Fairness with Bandwidth-Borrowing Scheme for a Two-Tier NEMO System

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Abstract. In this paper, we present a proportional fairness with bandwidth-borrowing (PFBB) scheme for a two-tier NEMO system. When traffic load is light, free-slot borrowing is employed to maximize system utilization. On the other hand, when traffic load is heavy and session arrival rates in different tiers are not proportional to their distributed areas, busy-slot borrowing is used to achieve proportional fairness. A mathematical model is built to analyze the performance in terms of the system utilization, blocking probabilities, and fairness index. Analytical results show that fairness index can be affected significantly, when session arrival rates in different tiers are varied.

Keywords: Proportional fairness, Traffic distributtion, Bandwidth borrowing, Makov chains, and NEMO.

1 Introduction

NEtwork MObility (NEMO) proposed by IETF is an integrated approach to maintain the connectivity of a mobile network so that internal mobile devices can perform seamless roaming between different Internet attachment points. Hierarchical NEMO architecture [1] plays an important role in improving the coverage of wireless communications, since it can effectively support large number of mobile devices roaming in different geographical areas. Hierarchical mobile networks were proposed in [2-3], where a mobile node (MN) attaches to an access router (AR) or a mobile router (MR), depending on the geographical area where it resides. In other words, an MN may set up a multimedia (video/audio/data) session to an AR if it is located in the service area of AR, and it may have to communicate indirectly with AR via a neighboring MR, if it is outside the service range of AR. Due to limited resources of a wireless NEMO system, it is important to provide an adequate bandwidth allocation strategy especially when there are insufficient network resources. As shown in [4-5], Channel-borrowing schemes were mainly focused on wireless cellular networks and they did not consider channel allocations in a multi-tier hierarchical NEMO system. By taking into account the effect of queuing times for different traffics, a Markov model proposed by Salih *et al.* [6] evaluated the performance of a two-tier cellular network. However, their works did not investigate how to apply fairness criterion to a multi-tier hierarchical

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NEMO system. Thus, many studies have dealt with different kinds of fairness, e.g., max-min fairness in [7] and proportional fairness in [8].

In this paper, the proposed proportional fairness with bandwidth-borrowing (PFBB) scheme endeavors to achieve balance between the fairness of bandwidth sharing and the improvement of system utilization. The ratio of session arrival rates between direct- (Tier-0) and indirect-link (Tier-1) in a two-tier NEMO system is assumed to be proportional to the ratio of MN distributed areas between Tier-0 and Tier-1. In light traffic, PFBB employs free-slot borrowing to maximize system utilization. On the other hand, when traffic load is heavy and the ratio of data-session arrival rates between Tier-0 and Tier-1 is not proportional to the MN distributed areas, busy-slot borrowing scheme is employed to achieve proportional fairness. A mathematical model with 6-D Markov chains is built to evaluate the PFBB performance in terms of the system utilization, blocking probability, and fairness index.

The rest of this paper is organized as follows. In Section 2, we describe the traffic model and the proposed PFBB scheme in a two-tier hierarchical NEMO system. In Section 3, we introduce the 6-D Markov model to analytically derive the performance metrics, such as system utilization, proportional fairness index, and session blocking probability. Numerical results and discussions are presented in Section 4. Finally, Section 5 contains our concluding remarks.

2 System Models

For a NEMO network, assuming each MN maintains only one session at a time and each AR has a capacity of *C* slots allocated for serving the session requests of MNs. A logical view of the NEMO scheme, shown in Fig. 1, an MN can establish a direct-link (Tier-0) session to an AR if it is located within the service area of the AR. In addition, the MN also can establish an indirect-link (Tier-1) session via the intermediate MR to the adjacent AR. Session 1 and Session 3 are Tier-0 connections of high-speed and low-speed levels, respectively. Similarly, Session 2 and Session 4 are Tier-1 connections of high-speed and low-speed levels, respectively. Therefore, four kinds of traffic types in Fig. 1, Session 1, Session 2, Session 3, and Session 4, are expressed in terms of *Type-H0*, *Type-H1*, *Type-L0*, and *Type-L1*, respectively.

In our previous works [9], a NEMO network is assumed to be homogeneous such that session generations are uniformly distributed in the service area of AR. In fact, unfair sharing of wireless bandwidth is occurred while the unequal traffic distribution in the service area, i.e., session generations of different traffic types are non-proportional to their distributed areas. Therefore, impact of fairness on the sharing wireless bandwidth between Tier-0 and Tier-1 is our major concern.

A logical view of distributed areas of Tier-0 and Tier-1 can be depicted in Fig. 2. For simplicity, the service areas of AR and MR are assumed to circles and the radii of AR and MR are denoted as R and r, respectively. The distributed area of Tier-0 (A_0) can be covered within the whole service area of AR because any generated Tier-0 session is lived only if the associated MN is located within the service area of AR. When the MN moves across the border of service area of AR (MN_N), it can send a session request of Tier-1 to AR via an intermediate MR that can communicate with AR and MN at the same time. As the MN moves across the border of service area of

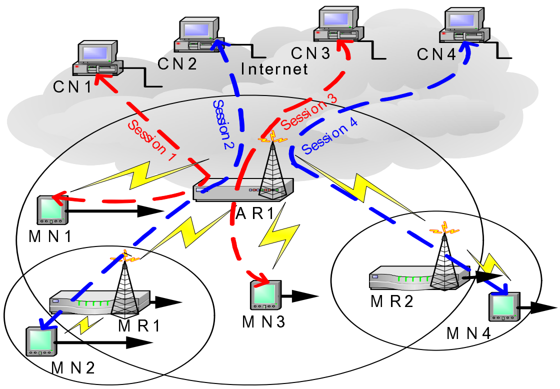

Fig. 1. A two-tier hierarchical NEMO system

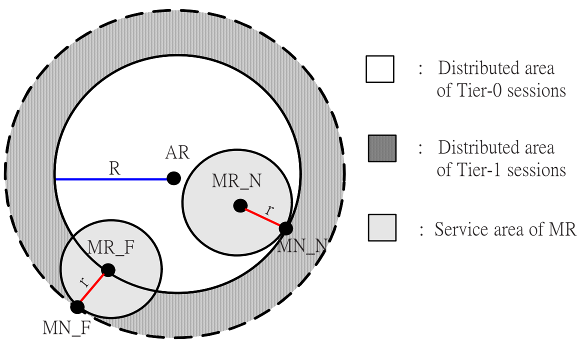

Fig. 2. Distributed areas in Tier-0 and Tier-1

MR (MN_F) and the MR also moves across the border of service area of AR (MR_F), the associated Tier-1 session would become invalid since the intermediate MR no longer communicates with AR and MN simultaneously. Therefore, the shaded region in Fig. 2 can represent the distributed area of Tier-1 (A_1). Thus, the distributed-area ratio of A_0 to A_1 (r_D) can be expressed as in Eq. (1).

$$r_D = \frac{R^2}{(R+r)^2 - R^2}. \quad (1)$$

Considering a single AR model in a two-tier NEMO network, total number of C slots can be divided into two partitions: Tier-0 slots with the capacity of C_0 and Tier-1 slots with the capacity of C_1. To achieve fair sharing of wireless bandwidth between Tier-0 and Tier-1, the capacity ratio of C_0 to C_1 is compatible with the distributed-area ratio of A_0 to A_1 (r_D), i.e., C_0 / $C_1 = r_D$. A bandwidth borrowing is active when the ratio of slot occupancies between Tier-0 and Tier-1 is incompatible with r_D. A borrowing limit (B), with the range from 0 to the minimum of C_0 and C_1, explicitly implies the maximum slots for each traffic type involved in bandwidth borrowing. If B is equal to 0, it can be viewed as the original scheme without performing borrowing.

Two kinds of borrowing mechanisms can be explained as below. A free-slot borrowing is employed for increasing system utilization under the light traffic load. Any free Tier-0/Tier-1 slots can be reallocated to Tier-1/Tier-0 sessions on their arrival if the original capacities for Tier-0/Tier-1 are fully used. However, reallocating free slots of different traffic types will lead to non-proportional ratio of slot occupancies between Tier-0 and Tier-1. Therefore, performing free-slot borrowing by *Type-H0* and *Type-H1* sessions is more appropriate than that by *Type-L0* and *Type-L1*. Under heavy traffic load, busy Tier-1 slots can be reallocated to Tier-0 sessions on their

```
// When a session arrives
Case 'H0':  // a Type-H0 session arrives
   If (S0<C0 and S <C)
      i=i+1;
   Else if (S0 ≥ C0 and S0<C0+B)
      If (S<C) // performing free-slot borrowing
         i= i+1;
      Else  // S=C
         Reject it;
   Else if (S0<C0 and S=C)
      If (w>0)  // perform busy-slot borrowing
         i=i+1, w=w–1, y=y+1;
      Else    // perform busy-slot borrowing
         i=i+1, x=x–1, z=z+1;
Case 'L0':  // a Type-L0 session arrives
   If (S0<C0 and S<C)
      j=j+1;
   Else if (S0 ≥ C0 and S0 < C0+B)
      Reject it;
   Else if (S0<C0 and S=C)
      If (x>0)   // perform busy-slot borrowing
         j=j+1, x=x–1, z=z+1;
      Else      // perform busy-slot borrowing
         j=j+1, w=w–1, y=y+1;
Case 'H1':  // a Type-H1 session arrives
   If (S1<C1 and S<C)
      w=w+1;
   Else if (S1 ≥ C1 and S1<C1+B)
      If (S<C)   // perform free-slot borrowing
         w=w+1;
      Else  // S=C
         Reject it;
      Else if (S1<C1 and S=C)
         y=y+1;

Case 'L1':  // a Type-L1 session arrives
   If (S1<C1 and S<C)
      x=x+1;
   Else if (S1 ≥ C1 and S1<C1+B)
      Reject it;
   Else if (S1<C1 and S=C)
      z=z+1;
// When a served session leaves
Case 'H0':  //a served Type-H0 session leaves
   If (y ≠ 0)
      i=i-1, w=w+1, y=y–1;
   Else if (z ≠ 0)
      i=i-1, x=x+1, z=z-1;
   Else
      i=i–1;
Case 'L0':  //a served Type-L0 session leaves
   If (z ≠ 0)
      j=j-1, x=x+1, z=z–1;
   Else if (y ≠ 0)
      j=j-1, w=w+1, y=y-1;
   Else
      i=i–1;
Case 'H1':  //a served Type-H1 session leaves
   If (y ≠ 0)
      y=y–1;
   Else if (z ≠ 0)
      w=w-1, x=x+1, z=z-1;
   Else
      w=w–1;
Case 'L1':  //a served Type-L1 session leaves
   If (z ≠ 0)
      z=z-1;
   Else if (y ≠ 0)
      x=x-1, w=w+1, y=y-1;
   Else
      x=x–1;
// When a queued session leaves
Case 'H1': //a queued Type-H1 session leaves
   y=y–1;
Case 'L1':  //a queued Type-L1 session leaves
x=x–1;
```

Fig. 3. Slot allocation algorithms in PFBB

arrival when the ratio of slot occupancies between Tier-0 and Tier-1 is incompatible with the distributed-area ratio of A_0 to A_1 (r_D). If the ratio of slot occupancies between Tier-0 and Tier-1 becomes larger than r_D, it would perform busy-slot barrowing mechanism from the served Tier-1 sessions to the arriving Tier-0 ones in balance of the slot occupancies of both traffic types.

Nine parameters, $i, j, w, x, y, z, S_0, S_1$, and S are used to show the status of the employed sessions when performing bandwidth borrowing. First, i , j, w, and x are the numbers of *Type-H0* , *Type-L0* , *Type-H1, Type-L1* sessions allocated in the slots, respectively. Then, y and z are the numbers of *Type-H1* and *Type-L1* sessions queued in the buffer, respectively. S_0 is the sum of the number of *Type-H0* and *Type-L0* sessions allocated. S_1 is the sum of the number of *Type-H1* and *Type-L1* sessions allocated. Finally, S is the sum of the number of all sessions allocated. The value ranges of these discrete parameters are $i \in [0, C_0 + B]$, $j \in [0, C_0]$, $w \in [0, C_1 + B]$, $x \in [0, C_1]$, $y \in [0, B]$, $z \in [0, B]$, $S_0 \in [0, C_0 + B]$, $S_1 \in [0, C_1 + B]$, and $S \in [0, C]$.

Pseudo-code of the proposed PFBB is shown in Fig. 3. Any arriving Tier-0/Tier-1 sessions are allocated with their original capacities if free Tier-0/Tier-1 slots exist. When S_0 (S_1) is reached C_0 (C_1), an arriving *Type-L0* (*Type-L1*) session is rejected while a *Type-H0* (*Type-H1*) session on its arrival is reallocated a free Tier-1 (Tier-0) slot by free-slot borrowing. When S equals C and S_0 is smaller than C_0, after performing busy-slot borrowing, next arriving Tier-0 session is reallocated with the busy Tier-1 slots and the original occupied Tier-1 sessions will be interrupted and queued in their corresponding MRs. On the other hand, Tier-1 sessions on their arrival will be queued to wait for the next free slots if S_1 is smaller than C_1.

3 Mathematical Analysis

3.1 Markov Model

An analytical model of the proposed PFBB is built with 6-D Markov chains, where each state (i, j, w, x, y, z) exists as long as the following four constraints are met.

1. $\forall i, j, \ \ i + j \le C_0 + B$.
2. $\forall w, x, \ \ w + x \le C_1 + B$.
3. $\forall i, j, w, x, y, z, \ \ i + j + w + x + y + z \le C + B$.
4. If $i + j + w + x < C, \ \ y + z = 0$.

Furthermore, the following assumptions are also made in the traffic model: The data-session arrival rates of Tier-0 and Tier-1 are independent Poisson processes with mean λ_0 and λ_1, respectively. The mean speed of MNs in the NEMO system is assumed to be constant, v, and the speed ratio between high- and low-mobility MNs is also assumed to be constant, R_v. The mean speeds of high- and low-mobility MNs (v_H, v_L) can be calculated as $2vR_v/(R_v+1)$ and $2v/(R_v+1)$, respectively. The ratio of data-session arrival rates between high- and low-speed MNs is assumed to be constant, R_λ. The duration time of each session (T_d) is exponentially distributed with a mean $1/\mu$. The residence times of Tier-0 and Tier-1 sessions ($1/\tau_0$, $1/\tau_1$) can be simply derived by $\pi R/2v$ and $\pi r/2v$, respectively, where R and r are the radii of AR's and MR's service area. The residence times of *Type-H0*, *Type-L0*, *Type-H1*, and *Type-L1* sessions ($1/\tau_{H0}$, $1/\tau_{L0}$, $1/\tau_{H1}$, $1/\tau_{L1}$) are obtained by $\pi R/2v_H$, $\pi R/2v_L$, $\pi r/2v_H$, and $\pi r/2v_L$, respectively. The data-session service times (T_s) are also exponentially distributed with means $1/(\mu + \tau')$, where τ' is defined as

$$\tau' = \begin{cases} \tau_{H0}, & \text{for a } \mathit{Type\text{-}H0} \text{ session.} \\ \tau_{L0}, & \text{for a } \mathit{Type\text{-}L0} \text{ session.} \\ \tau_{H1}, & \text{for a } \mathit{Type\text{-}H1} \text{ session.} \\ \tau_{L1}, & \text{for a } \mathit{Type\text{-}L1} \text{ session.} \end{cases} \quad (2)$$

The queuing times of *Type-H1*, and *Type-L1* sessions ($1/\tau_{QH}$, $1/\tau_{QL}$) is also assumed exponentially distributed with means τ_{QH} and τ_{QL}, respectively, and can be denoted as:

$$\tau_{QH} = \frac{(2\lambda_{H1} + \lambda_{H0} + \lambda_{L0})\tau_{H1}}{2(\lambda_{H1} + \lambda_{H0} + \lambda_{L0})}. \quad (3)$$

$$\tau_{QL} = \frac{(2\lambda_{L1} + \lambda_{H0} + \lambda_{L0})\tau_{L1}}{2(\lambda_{L1} + \lambda_{H0} + \lambda_{L0})}. \quad (4)$$

Here, the borrowing probability of *Type-H1* session is assumed to be equal to the borrowing probability of *Type-L1* session and the mean queueing time of *Type-H1* (*Type-L1*) session can be simply expressed by the products of the data-session service time of *Type-H1* (*Type-L1*) and the ratio of data-session arrival rates among *Type-H1* (*Type-L1*), *Type-H0*, and *Type-L0*.

3.2 Balance Equations

Let $P(\mathbf{n})$ be the steady-state probability of state (i, j, w, x, y, z), where $\mathbf{n} \equiv [i, j, w, x, y, z]$. To facilitate the expression of balance equations, two indicator functions are used.

$$I_0(a,b) = \begin{cases} 1 & a \neq b \\ 0 & a = b \end{cases}. \quad (5)$$

$$I_1(a,b) = \begin{cases} 1 & a = b \\ 0 & a \neq b \end{cases}. \quad (6)$$

The steady-state balance equations can be divided into the following six cases.

1. E_1 ($0 \le i + j < C_0$, $0 \le w + x < C_1$, and $y + z = 0$): the arriving Tier-0 and Tier-1 sessions will be allocated to their free slots in original capacities.
2. E_2 ($C_0 \le i + j \le C_0 + B$, $i + j + w + x < C$, and $y + z = 0$): only *Type-H0* and Tier-1 sessions can be allocated to the free Tier-1 slots due to Tier-0 slots have been fully occupied.
3. E_3 ($C_1 \le w + x \le C_1 + B$, $i + j + w + x < C$, and $y + z = 0$): Tier-1 slots have been fully used and only *Type-H1* and Tier-0 sessions can be allocated to the free Tier-0 slots.

4. E_4 ($C_0 \le i+j < C_0+B$, $i+j+w+x=C$, and $0 \le y+z < B$): the arriving Tier-1 sessions will be queued in corresponding MRs to wait for the next released slots.
5. E_5 ($C_1 \le w+x < C_1+B$, $i+j+w+x=C$, and $0 \le y+z < B$): Tier-0 sessions on their arrival can be reallocated to the busy Tier-1 slots.
6. E_6 ($i+j+w+x=C$, and $y+z=B$): all the arriving Tier-0 and Tier-1 sessions will be rejected.

We can obtain the steady-state probabilities by solving the steady-state balanced equations with the following initial condition.

$$\sum_{k=1}^{6} P(\mathbf{n} \mid \mathbf{n} \in E_k) = 1. \tag{7}$$

3.3 Performance Metrics

To evaluate the proposed PFBB, three performance metrics, system utilization, proportional fairness index, and session blocking probabilities are derived. System utilization (U) in Eq. (8) is defined as the normalized throughput.

$$U = \frac{1}{C} \sum_{k=1}^{6} \left[(i+j+w+x) P(\mathbf{n} \mid \mathbf{n} \in E_k) \right]. \tag{8}$$

Proportional fairness index (PFI) in Eq. (9) is defined to determine how fair the system model is. It can be estimated by the ratio of two terms, the ratio of slot occupancies between Tier-0 and Tier-1 and the distributed-area ratio of Tier-0 to Tier-1. For the fairest case, PFI = 1, As PFI is larger than 1, the ratio of slot occupation between Tier-0 and Tier-1 is not proportional to their distributed areas. If PFI is smaller than one, Tier-1 sessions gets more bandwidth than they are expected.

$$PFI = \frac{\sum_{k=1}^{6} \left[(i+j) P(\mathbf{n} \mid \mathbf{n} \in E_k) \right]}{r_D \sum_{k=1}^{6} \left[(w+x) P(\mathbf{n} \mid \mathbf{n} \in E_k) \right]}. \tag{9}$$

In the proposed PFBB, any Tier-0 session will be blocked on its arrival if total number of associated slot occupancy is greater than or equal to (C_0+B). Furthermore, we can distinguish between the probabilities of *Type-H0* and *Type-L0* with the condition of *E2*. Similarly, Tier-1 sessions will be blocked if total number of associated slot occupancy is greater than or equal to (C_1+B). Session blocking probabilities of *Type-H0*, *Type-L0*, *Type-H1*, and *Type-L1* are represented as

$$P_{b\_H0} = \left[\sum P(\mathbf{n} \mid \mathbf{n} \in E_{2,1}) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_4) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_6) \right] \tag{10}$$

$$P_{b\_L0} = \left[\sum P(\mathbf{n} \mid \mathbf{n} \in E_{2,2}) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_4) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_6) \right]$$

$$P_{b\_H1} = \left[\sum P(\mathbf{n} \mid \mathbf{n} \in E_{3,1}) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_5) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_6) \right]$$

$$P_{b\_L1} = \left[\sum P(\mathbf{n} \mid \mathbf{n} \in E_{3,2}) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_5) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_6) \right],$$

where $E_{2,1} = \left\{ \mathbf{n} \middle| \sum_{E_2} i + j = C_0 + B \right\}$, $E_{2,2} = \left\{ \mathbf{n} \middle| \sum_{E_2} i + j \geq C_0 \right\}$, $E_{3,1} = \left\{ \mathbf{n} \middle| \sum_{E_3} w + x = C_1 + B \right\}$, and

$$E_{3,2} = \left\{ \mathbf{n} \middle| \sum_{E_3} w + x \geq C_1 \right\}.$$

Then, session blocking probability of Tier-0 ($P_{b\text{-}0}$) can be introduced to the union of the blocking probabilities of *Type-H0* and *Type-L0.* Similarly, session blocking probability of Tier-1 session ($P_{b\text{-}1}$) can be viewed as the union of the blocking probabilities of *Type-H1* and *Type-L1*. They are shown as follows.

$$\begin{aligned} P_{b\_0} &= \left[\frac{\lambda_{H0}}{\lambda_0} \sum P(\mathbf{n} \mid \mathbf{n} \in E_{2,1}) + \frac{\lambda_{L0}}{\lambda_0} \sum P(\mathbf{n} \mid \mathbf{n} \in E_{2,2}) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_4) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_6) \right] \\ P_{b\_1} &= \left[\frac{\lambda_{H1}}{\lambda_1} \sum P(\mathbf{n} \mid \mathbf{n} \in E_{3,1}) + \frac{\lambda_{L1}}{\lambda_1} \sum P(\mathbf{n} \mid \mathbf{n} \in E_{3,2}) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_5) + \sum P(\mathbf{n} \mid \mathbf{n} \in E_6) \right]. \end{aligned} \quad (11)$$

4 Performance Evaluation

By running on the MATLAB tool, we give a numerical example. System parameters used in the example are listed in Table 1.

Table 1. Parameters used in the numerical analysis

Parameters	Values	Parameters	Values
C	10	λ_0	0.25 (1/s)
B	5	λ_1	0.25 (1/s)
R	5000 (m)	R_λ	1
R	2000 (m)	v	20 (m/s)
T_d	1/180 (s)	R_v	1.5

The results of system utilization under different area ratios of A_0 to (A_0 + A_1) are plotted in Fig. 4. When the area ratio of A_0 to (A_0 + A_1) is increased, the system utilization (U) in PFBB declines as the ratio of session arrival rates between Tier-0 and Tier-1 is decreased from 1/3 to 1/6. It is a trade-off between achieving the proportional fairness and maximizing the system utilization when traffic load is heavy. Proportional fairness indexes (*PFI*) under different data-session arrival rates and different ratios of session arrival rates is shown in Fig. 5. As can be observed, both schemes, if in smaller ratio of data-session arrival rate ($\lambda = 0.01$), cannot reach the target fairness index since the system is under loaded. Higher ratio of data-session arrival rate ($\lambda_0/\lambda_1 = 3$) has benefit in increasing the slot occupancies of Tier-1. As the session arrival rate increases, however, the *PFI* in PFBB is close to the target no matter the ratio of data-session arrival rates is higher or lower.

Referring to Equation (11), Fig. 6 and Fig. 7, respectively, show the blocking probabilities of Tier-0 and Tier-1 sessions. $P_{b\text{-}0}$ and the $P_{b\text{-}1}$ monotonically increase with respect to the increase of session arrival rate ($\lambda_0 + \lambda_1$). $P_{b\text{-}0}$ in PFBB is always higher than that in original scheme when the ratio of session arrival rates is high ($\lambda_0/\lambda_1 = 3$). On the contrary, Tier-0 sessions in PFBB get more bandwidth than that in the original scheme when the ratio of session arrival rate is low ($\lambda_0/\lambda_1 = 1/3$).

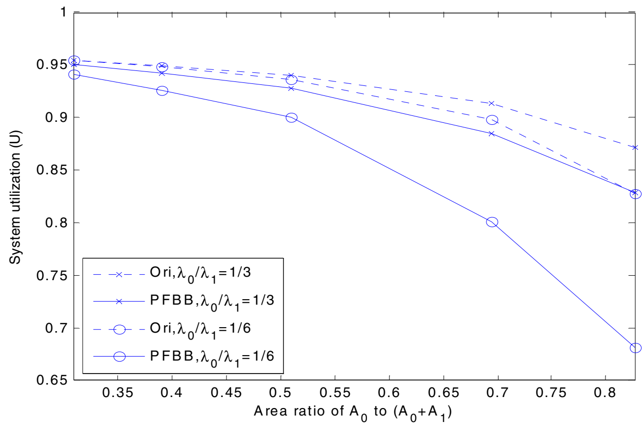

Fig. 4. System utilization vs area ratio (Tier-0)

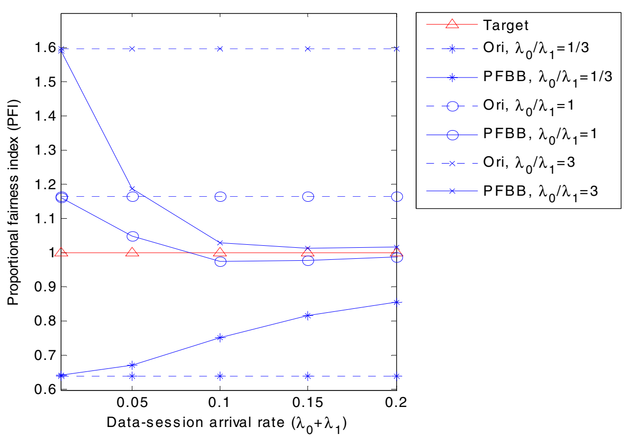

Fig. 5. Proportional fairness index

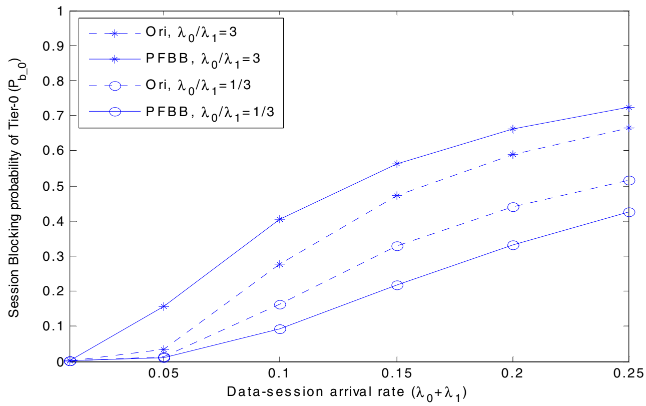

Fig. 6. Session blocking probability of Tier-0

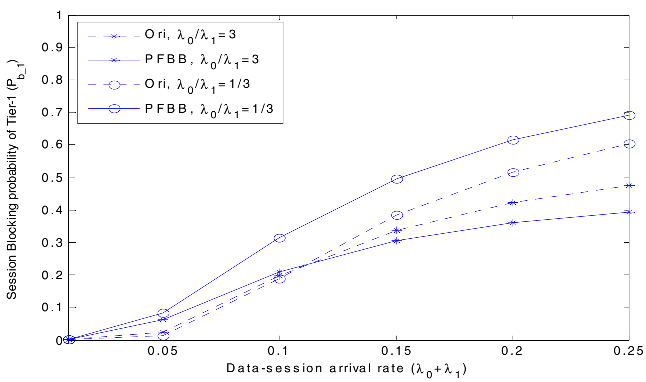

Fig. 7. Session blocking probability of Tier-1

5 Conclusions

We have presented a proportional fairness with bandwidth-borrowing scheme in two-tier hierarchical NEMO networks. A free-slot borrowing is employed to maximize system utilization by borrowing available slots when the traffic load is light. In our design, a busy Tier-1 slot can be borrowed to an arriving Tier-0 session if the ratio of slot occupancies between Tier-0 and Tier-1 is smaller than their distributed-area ratio while the NEMO network becomes congested. For the purpose of validation, an analytical model was built to compare the performance between our proposed scheme and the original scheme. From the analytical results, we have demonstrated that the proposed model can achieve the goal of fairly bandwidth sharing between Tier-0 and Tier-1 according to their distributed-area ratio.

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