Fair Scheduling of Two-Hop Transmission with Energy Harvesting

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Abstract. In this paper, we consider a two-hop network with a source node (SN) and a relay node (RN) who want to communicate data to a destination node (DN). The SN cannot be directly connected to the DN, but rather is connected only via the RN. The RN does not have an external source of energy, and thus needs to harvest energy from the SN to communicate, while the SN has an external source of energy and can harvest energy straight from it. Thus, a dilemma for the SN arises: how much to share harvested energy with the RN to make it relay the SN's data to the DN. Fair performing of their communication tasks is considered as an incentive for the SN and the RN to cooperate. The optimal α fair schedule is found for each α. It is shown that an altruistic strategy for one of the nodes comes in as a part of the cooperative solution (corresponding $\alpha = 0$), while the maxmin strategy (corresponding α tending to infinity) is proved to be egalitarian. Using Nash bargaining over the obtained continuum of fair solutions, we design a trade-off strategy.

Keywords: Adhocnets · Energy harvesting · Fairness · Bargaining

1 Introduction

Using nodes powered by green energy in wireless networks (e.g., sensor networks) allows one to prolong their lifetime and increase their sustainability. Besides of harvesting energy from such sources of green energy as solar radiation or piezoelectric devices, nodes can also harvest energy using radio frequency (RF) transmissions from other wireless nodes [13]. Such energy transfer technologies can serve as a basis for nodes cooperating, thereby leading to improved overall network performance [18]. In [11], a problem of two-hop relaying with energy harvesting nodes was considered and the optimal transmission scheme with the source having a single energy packet was found for a half-duplex relay. In [16], a directional waterfilling algorithm was derived for a Gaussian fading channel with an energy harvesting transmitter. In [17], a game-theoretical approach was used to minimize the non-renewable energy consumption in a multi-tier cellular network. In [19], a stochastic energy trading game was developed with two types of energy-harvesting devices: sellers harvesting more energy than they can

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use, and buyers that have to buy energy to support their required communication services. In [20], an optimal packet scheduling problem for a single-user transmission with discrete energy harvesting was considered.

In [18], a question was put forward: *how can one make the nodes cooperate?* To find an answer, in [18], a game-theoretical model for the relay node, powered solely by wireless energy transfer from the source node, was suggested. A pricing scheme was considered as an incentive for cooperation. It was shown that altruistic operation of the nodes can be facilitated by the proposed pricing. In this paper, we consider fairness (namely, α-fairness) in performing the communication tasks by the nodes as an incentive to cooperate. The optimal α-fair schedule is found for each α. We show that an altruistic strategy for one of the nodes comes in as a part of the cooperative solution corresponding to a boundary value of α equals to zero. The benefits of a cooperative strategy is that it maximizes total network performance, while the drawback is that it is not energy safe. On the other hand, the benefits of a maxmin strategy (corresponding to the other boundary case of α tending to infinity) is that it is egalitarian and energy safe compared to cooperative, but the drawbacks of the maxmin strategy is that it supports lower total network performance. Hence there is a fundamental problem associated with selecting a fairness coefficient, which arises from the trade-off between altruistic and egalitarian strategies. A core contribution of this paper is that, by applying Nash bargaining approach, we design such a trade-off strategy.

The organization of this paper is as follows: in Sect. 2, a model where the source node sends data directly to the destination node is studied. In Sect. 3, the model is generalized for the scenario where transmission is performed via a relay node. The α-fair schedule is found for each α. In Sect. 4, trade-off value for fairness coefficient using Nash barging approach is obtained. Finally, in Sect. 5, conclusions are offered, and, in Appendix A, the proof of the obtain results are given.

2 The Source Node Sends Data Directly to the Destination

Let a source node (SN) send data to a destination node (DN), but have to harvest energy from an external source. During energy harvesting the SN cannot send data. The rate of energy harvesting p_h, reflects the energy harvested per time unit, is fixed. The goal of the SN is to harvest energy to maintain sending data to the DN within a time slot of duration T. The SN, to send data, applies a fixed power p_s per unit of time, called power (transmission) rate. Thus, the time slot is split into two phases: (a) *energy harvesting* (duration T_h) and (b) *communication* (duration T_s), where

$$T_h + T_s = T. \tag{1}$$

The total energy accumulated by the SN within energy harvesting phase is given as follows:

$$E = p_h T_h. \tag{2}$$

The total energy p_sT_s used by the SN in communication phase cannot be larger than the accumulated energy E, i.e., by (2),

$$p_sT_s \le p_hT_h. \tag{3}$$

Due to the SN, to send data, applies a fixed power p_s per unit of time within the communication phase having duration T_s, the total throughput is given as follows:

$$v(\boldsymbol{T}) = T_s \ln(1 + h_sp_s) \text{ with } \boldsymbol{T} = (T_h, T_s). \tag{4}$$

Then, in the framework of this model, two sequential optimization problems arise: (a) to optimize the phase schedule to maximize throughput for a fixed power rate, and (b) to optimize the power transmission rate to send data.

(a) To optimize the phase schedule to maximize throughput for a fixed power rate: Here, the goal of the SN is to find the phase schedule $\boldsymbol{T} = (T_h, T_s)$ to maximize throughput (4) for a fixed p_s.

Theorem 1. *For a fixed power rate p_s, the optimal phase schedule $\boldsymbol{T}$ is given as follows:*

$$T_s = p_hT/(p_h + p_s) \; and T_h = p_sT/(p_h + p_s). \tag{5}$$

This schedule yields the total SN throughput as a function of p_s is equal to:

$$\overline{v}(p_s) = p_hT \ln(1 + h_sp_s)/(p_h + p_s). \tag{6}$$

(b) To optimize the power transmission rate to send data. Here, the power rate p_b is considered as a variable controlled by the SN. Thus, the phase schedule (5) and the total SN's throughput (6) are functions of p_s. The goal of the SN is to find p_s to maximize this total SN throughput.

Theorem 2. *The optimal power rate to send data is equal to:*

$$p_s = (\exp\left(LambertW((h_sp_h - 1)/e) + 1\right) - 1)/h_s.$$

In particular, Theorem 2 implies that the optimal power rate does not depend on duration of time slot. Figure 1(A) illustrates that an increase in quality of communication reflected by fading channel gains h_b leads to an increase in the SN throughput. It is interesting that the SN achieves this increase by reducing

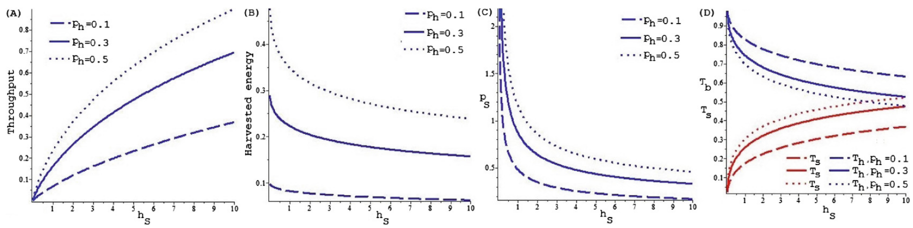

Fig. 1. Throughput, harvested energy, power rate and schedule as functions of h_s.

energy harvesting (Fig. 1(B)). This could be done by applying *energy safe* schedule, namely, by reducing the power transmission rate (Fig. 1(C)) while increasing the duration of transmission (Fig. 1(D)). Thus, here, like in economics where investment in public infrastructure fuels economic growth and attracts new technologies, improving network infrastructure reflected by improving channel gains (e.g. better antennas) encourages using energy safe strategies.

3 The Source Node Sends Data to the Destination Node via a Relay Node

In this Section extend the model for a two-hop scenario where the SN cannot send data directly to the DN but only via a relay node (RN). The RN does not have an external source of energy, and needs to harvest energy from the SN to communicate, while the SN has such external source of energy and can harvest energy straight from it. Thus, the harvested energy is a resource for the SN to communicate with the DN as well as the resource to motivate the RN to cooperative with the SN in performing this task. As incentive to cooperate we consider fair performing of communication tasks by the SN and the RN.

Let us describe the model in detail. We assume that the SN and the RN cannot perform their energy harvesting and communication operations simultaneously. All of the operation takes place within a time slot with duration T. Thus, the time is split into four phases: (a) *energy harvesting by the SN* from an external source (duration T_h), (b) *energy harvesting by the RN* from the SN (duration T_{hr}), (c) *sending data by the SN to the DN via the RN* (duration T_{sd}), (d) *sending data by the RN to the DN* (duration T_{rd}). Thus,

$$T_h + T_{hr} + T_{sd} + T_{rd} = T. \tag{7}$$

Let h_{rd} be the fading channel gains for the RN to send data to the DN. Let h_{sr} be the fading channel gains for the SN to send data or energy to the RN. Let $h_{sd} := h_{sr}h_{rd}/(1 + h_{rd})$ be the fading channel gains for the SN to send data to the DN via the RN. Let p_s be the power rate to send either energy supply to the RN or to send data to the DN via the RN by the SN. Let p_r be the power rate to send data by the RN to the DN.

The total energy accumulated by the SN during the energy harvesting phase is:

$$E = p_h T_h. \tag{8}$$

The total energy E_r sent by the SN to the RN during energy harvesting by the RN phase is

$$E_r = p_s T_{hr}, \tag{9}$$

while the total energy $\overline{E}_r$ accumulated by the RN for this phase is

$$\overline{E}_r = \gamma h_{sr} p_s T_{hr}, \tag{10}$$

where γ is the coefficient of energy accumulation.

The total energy used by the SN to send data to the DN via the RN is given as follows:

$$E_{sd} = T_{sd} p_s, \tag{11}$$

which yields the total SN throughput, given as follows:

$$v_s = T_{sd} \ln(1 + h_{sd} p_s). \tag{12}$$

The total energy $T_{rd} p_r$ employed by the RN to send data to the DN has to be equal to the energy $\overline{E}_r$ harvested from the SN, i.e.,

$$\overline{E}_r = T_{rd} p_r, \tag{13}$$

which yields the total RN throughput given as follows:

$$v_r = T_{rd} \ln(1 + h_{rd} p_r). \tag{14}$$

Thus, a dilemma for the SN arises *how much harvested energy has to be used for communication and how much to share with the RN to make it relay the SN's data to the DN*? As an incentive for the SN and the RN to cooperate, we consider the fair performing of communication tasks for each of them, and the α -fairness utility is considered as such a fairness criterion. Thus, the goal of the SN is to find schedule $\boldsymbol{T} = (T_h, T_{hr}, T_{sd}, T_{rd})$ to fulfil fairly each of these communication tasks. In the considered model, the α-fairness utility for these communication tasks is given as follows: $v(\boldsymbol{T}) = (v_r(\boldsymbol{T}))^{1-\alpha}/(1-\alpha) + (v_s(\boldsymbol{T}))^{1-\alpha}/(1-\alpha)$ for $\alpha \neq 1$ and $v(\boldsymbol{T}) = \ln(v_r(\boldsymbol{T})) + \ln(v_r(\boldsymbol{T}))$ for $\alpha = 1$. The α-fair schedule is given as the solution of the following problem:

$$\text{maximize } v(\boldsymbol{T}), \text{ subject to} \tag{15}$$

$$T_h \geq 0,\ T_{hr} \geq 0,\ T_{sd} \geq 0,\ T_{rd} \geq 0, \tag{15a}$$

$$T_h + T_{hr} + T_{sd} + T_{rd} = T, \tag{15b}$$

$$p_h T_h = T_{hr} p_s + T_{sd} p_s, \tag{15c}$$

$$\gamma h_{sr} p_s T_{hr} = T_{rd} p_r. \tag{15d}$$

Note that α-fairness criterion provides a unified framework for considering a wide array of fairness considerations, ranging from maximizing cooperative solution (for $\alpha = 0$) through proportional fairness (for $\alpha = 1$) to the maxmin solution (for α tending to infinity). As a survey on fairness criteria applied in wireless network we refer to [12], while as examples of α-fairness criteria, we refer the reader to [15] for a throughput assignment problem, and to [9] for bargaining over the fair trade-off between secrecy and throughput in OFDM communications. In [5,7,8], maxmin strategies were designed as solution of the corresponding zero-sum games. In [14], in the context of LTE-A networks, cooperative bargaining solutions for resource allocation over the available component carriers was investigated. In [10], bargaining problem over fair performing dual radar and communication task was solved. In [1,6], fair power control was applied for resources allocation by base station under uncertainty. In [3,4], fair channel sharing strategies by WiFi and LTE-U networks were designed.

Theorem 3. *(a) The α-fair schedule $\boldsymbol{T}_\alpha = (T_{h,\alpha}, T_{hr,\alpha}, T_{sd,\alpha}, T_{rd,\alpha})$ is unique and given as follows:*

$$\begin{aligned} T_{h,\alpha} &= T\frac{P_s A_s^{1/\alpha}/L_s + P_s P_r A_r^{1/\alpha}/L_r}{A_s^{1/\alpha-1} + A_r^{1/\alpha-1}},\ T_{hr,\alpha} = T\frac{P_r A_r^{1/\alpha}/L_r}{A_s^{1/\alpha-1} + A_r^{1/\alpha-1}}, \\ T_{sd,\alpha} &= T\frac{A_s^{1/\alpha}/L_s}{A_s^{1/\alpha-1} + A_r^{1/\alpha-1}},\ T_{rd,\alpha} = T\frac{A_r^{1/\alpha}/L_r}{A_s^{1/\alpha-1} + A_r^{1/\alpha-1}}, \end{aligned} \tag{16}$$

$$\begin{aligned} &\text{where } L_s := \ln(1 + h_{sd}p_s),\ L_r := \ln(1 + h_{rd}p_r),\ P_r := p_r/(\gamma h_{sr}p_s), \\ &\qquad P_s := p_s/p_r,\ A_s := L_s/(1 + P_s),\ A_r := L_r/(1 + P_r(1 + P_s)). \end{aligned} \tag{17}$$

(b) The following relations hold between the SN throughput $v_{s,\alpha}$ and the RN throughput $v_{r,\alpha}$ corresponding to $\boldsymbol{T}_\alpha$:

$$v_{s,\alpha}/v_{r,\alpha} = (A_s/A_r)^{1/\alpha} \text{ and } v_{s,\alpha}/A_s + v_{r,\alpha}/A_r = T. \tag{18}$$

(c) The maxmin solution corresponds to α tending to infinity and is given as:

$$\begin{aligned} &v_{s,\infty} = v_{r,\infty} = v_\infty := T/(1/A_s + 1/A_r), \\ &\boldsymbol{T}_\infty = \left(\frac{T(P_s/L_s + P_s P_r/L_r)}{1/A_s + 1/A_r}, \frac{TP_r/L_r}{1/A_s + 1/A_r}, \frac{T/L_s}{1/A_s + 1/A_r}, \frac{T/L_r}{1/A_s + 1/A_r}\right). \end{aligned} \tag{19}$$

(d) The cooperative solution corresponds to $\alpha = 0$ and is given as:

$$\boldsymbol{T}_0 = \begin{cases} \left(\frac{TP_s}{1+P_s}, 0, \frac{T}{1+P_s}, 0\right), & A_s > A_r, \\ \left(\frac{TP_r}{1 + P_h(1 + P_s)}, \frac{TP_s P_r}{1 + P_r(1 + P_s)}, 0, \frac{T}{1 + P_r(1 + P_s)}\right), & A_s < A_r, \end{cases} \tag{20}$$

$$v_{s,0} = \begin{cases} TA_s, & A_s > A_r, \\ 0, & A_s < A_r, \end{cases} \quad v_{r,0} = \begin{cases} 0, & A_s > A_r, \\ TA_r, & A_s < A_r. \end{cases} \tag{21}$$

Thus, in the cooperative solution, either the SN or the RN has to be a full altruist totally sacrificing its own communication task in the name of reaching the largest joint throughput. While the maxmin solution equalizes both throughput, or, in the other words, it is aimed at the equality of outcomes for the nodes. Thus, the fairness coefficient reflects a trade-off between altruism and equality of outcome. Further, between the throughput as functions of α there is a liner relation (18), and an increase in one throughput yields a decrease in the other Fig. 2(C). Also, in the considered example, for $\alpha = 0$ the RD has to be altruist focusing only on the relaying operation. An increase in α results in (i) a decrease in the SN throughput, (ii) an increase in the RN throughput, and (iii) a decrease in energy harvesting by the SN. The latter means that full altruism of one of the nodes (the RN) leads to employing a less energy safe strategy by the other (the SN); while an increase in selfishness for the SN (reflected by an intention to get a larger throughput for itself) makes the SN reduce energy harvesting and to switch to a more energy safe strategy Fig. 2(B). Also, an increase in α makes the SN spend more time supplying the RN by energy, thereby supporting an increase in duration for the RN communication with the DN.

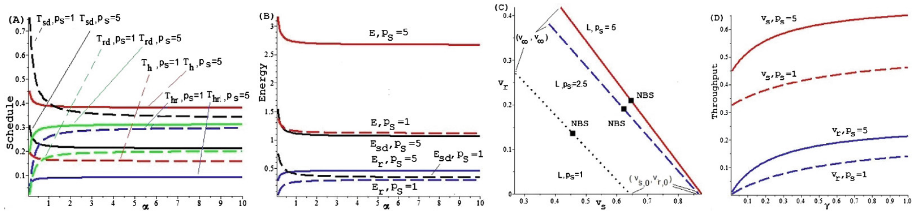

Fig. 2. (A) The α-fair schedule, (B) harvested energies used for harvesting and communication as functions on α, (C) relation between throughput in plane (v_s, v_r) for $T = 1$, $p_h = 7$, $p_r = 4$, $h_{sr} = 3$, $h_{rd} = 0.7$, $\gamma = 0.9$, $p_s \in \{1, 5\}$ and (D) bargaining throughput as function on γ.

4 Trade-off for Fairness Coefficient

Since, for each fixed α the fair solution $\boldsymbol{T}_\alpha$ is derived, a problem arises to find the most fair $\boldsymbol{T}_\alpha$. An answer to this problem will be obtained as the Nash bargaining solution (NBS) [2] over all of the fair throughputs [2]. *First* let us define the feasibility set $\boldsymbol{L}$ for all of the fair throughputs for the SN and the RN, i.e., $\boldsymbol{L} := \{(v_{s,\alpha}, v_{r,\alpha}) : \alpha \geq 0\}$. By (18) and (19), $\boldsymbol{L}$ is the line connecting the point $(v_{s,0}, v_{r,0})$ and the point (v_∞, v_∞). *Second* let $(v_s^d, v_r^d) = (\min\{v_{s,0}, v_\infty\}, \min\{v_{r,0}, v_\infty\})$ be the point composed by minimal throughput in $\boldsymbol{L}$. This point can be considered as *a disagreement point* [2]. Then, the NBS is given as given as $\arg\max\{NP(v_s, v_r) : (v_s, v_r) \in \boldsymbol{L}\}$ where $NP(v_s, v_r) := (v_s - v_s^d)(v_r - v_r^d)$ is called *the Nash product*.

Theorem 4. *The bargaining throughput is unique and given by*

$$(v_s, v_r) = \left(\frac{TA_sA_r}{2(A_s + A_r)}, \frac{TA_sA_r}{2(A_s + A_r)}\right) + \begin{cases} (TA_s/2, 0), & A_s > A_r, \\ (0, TA_r/2), & A_s < A_r. \end{cases}$$

The bargaining value for fairness coefficient is $\alpha = \ln(A_s/A_r)/\ln(v_r/v_s)$.

Figure 2(C) illustrates the NBS for $p_s \in 1, 2.5, 5$, while Fig. 2(D) illustrates that both throughput gains correspond to an increase in the coefficient of energy accumulation γ, and, thus, on an improvement for the RF technology us for energy harvesting.

5 Conclusions

To obtain insight into the cooperation between nodes with different sources of energy (from external sources or through radio frequency transmissions from other nodes), a simple two-hop network model was investigated. First we showed that, much like in economics where investment in public infrastructure fuels economic growth and attract new technologies, improving network infrastructure reflected by improved channel gains fuels the use of energy safe strategies. Then, based on α-fairness a problem of node cooperation was investigated. It is shown that an altruistic strategy for one of the nodes comes as a part of a cooperative solution, while the maxmin strategy is proven to be egalitarian. Using Nash bargaining over the obtained continuum of fair solutions, a trade-off between altruistic and egalitarian behaviors is found. Further, the gains associated with bargaining throughput correspond to an improvement in the RF technology used for energy harvesting.

A Appendix

Proof of Theorem 1. By (1) and (3), $T_s \le p_h T/(p_h + p_s)$. Then, due to v given by (4) is increasing on T_s, (5) follows. ■

Proof of Theorem 2. To find the optimal p_s we have to find derivation of v on p_s: $d\,v(p_s)/d\,p_s = (h_s(p_h + p_s)/(1 + h_s p_s) - \ln(1 + h_s p_s))\,T p_h/(p_h + p_s)^2$. Thus, $dv/dp_s\{>, =, <\}0$ if and only if $1 + a/x - \ln(x)\{>, =, <\}0$, where $x = 1 + h_s p_s$ and $a = h_s p_h - 1$. It is clear that $a > -1$ and $x \ge 1$. For a fixed $a > -1$ the function $1 + a/x - \ln(x)$ is decreasing on $x \ge 1$. Moreover, the equation $1 + a/x - \ln(x) = 0$ has the unique root $x = \exp(\mathrm{LambertW}\,(a/e) + 1)$, and the result follows. ■

Proof of Theorem 3. Since $v(\boldsymbol{T})$ is concave, to find the optimal $\boldsymbol{T}$ the KKT Theorem can be applied. First we define Lagrange function $L_{\omega_1,\omega_2,\omega_3}(\boldsymbol{T})$ with ω_1, ω_2 and ω_3 are Lagrange multipliers as follows:

$$\begin{aligned} L_{\omega_1,\omega_2,\omega_3}(\boldsymbol{T}) = {} & \frac{(T_{rd}L_r)^{1-\alpha}}{1-\alpha} + \frac{(T_{sd}L_s)^{1-\alpha}}{1-\alpha} + \omega_1(T - T_h - T_{hr} - T_{sd} - T_{rd}) \\ & + \omega_2(p_h T_h - T_{hr} p_s - T_{sd} p_s) + \omega_3(\gamma h_{sr} p_s T_{hr} - T_{rd} p_r). \end{aligned} \tag{22}$$

Then, for $\boldsymbol{T}$ to be optimal, besides of conditions (15b)–(15d), the following relations have to hold:

$$\partial L/\partial T_{rd} = L_r^{1-\alpha}/(T_{rd})^{\alpha} - \omega_1 - p_r\omega_3 \begin{cases} = 0, & T_{rd} > 0, \\ \le 0, & T_{rd} = 0, \end{cases} \tag{23}$$

$$\partial L/\partial T_{sd} = L_s^{1-\alpha}/(T_{sd})^{\alpha} - \omega_1 - p_s\omega_2 \begin{cases} = 0, & T_{sd} > 0, \\ \le 0, & T_{sd} = 0, \end{cases} \tag{24}$$

$$\partial L/\partial T_h = -\omega_1 + p_h\omega_2 = 0, \tag{25}$$

$$\partial L/\partial T_{hr} = -\omega_1 - p_s\omega_2 + \gamma h_{sr} p_s \omega_3 = 0. \tag{26}$$

By (25), we have that

$$\omega_2 = \omega_1/p_h. \tag{27}$$

By (26) and (27), we have that $\omega_3 = (1 + p_s/p_h)\omega_1/(\gamma h_{sr} p_s)$. Then, (17) and (23) yield that:

$$T_{rd} = \frac{L_r^{1/\alpha-1}}{(\omega_1 + p_r\omega_3)^{1/\alpha}} = \frac{L_r^{1/\alpha-1}}{(1 + P_r(1+P_s))^{1/\alpha}\omega_1^{1/\alpha}} = \frac{A_r^{1/\alpha-1}}{(1 + P_r(1+P_s))\omega_1^{1/\alpha}}. \tag{28}$$

By (24), in notation (17), we have that

$$T_{sd} = \frac{L_s^{1/\alpha-1}}{(\omega_1 + p_s\omega_2)^{1/\alpha}} = \frac{L_s^{1/\alpha-1}}{(1+P_s)^{1/\alpha}\omega_1^{1/\alpha}} = \frac{A_s^{1/\alpha-1}}{(1+P_s)\omega_1^{1/\alpha}}. \tag{29}$$

By (15d), (17) and (28) the following relation holds

$$T_{hr} = T_{rd}p_r/(\gamma h_{sr}p_s) = P_r T_{rd} = P_r A_r^{1/\alpha-1}/((1+P_r(1+P_s))\omega_1^{1/\alpha}). \tag{30}$$

By (15c), (29) and (30), using notation (17) we have that

$$T_h = \frac{p_s}{p_h}\left(T_{hr}+T_{sd}\right) = P_s\left(T_{hr}+T_{sd}\right) = \frac{P_s P_r A_r^{1/\alpha-1}}{(1+P_r(1+P_s))\omega_1^{1/\alpha}} + \frac{P_s A_s^{1/\alpha-1}}{(1+P_s)\omega_1^{1/\alpha}}. \tag{31}$$

Then, summing (28)–(31) and taking into account (15c) imply that $\omega_1^{1/\alpha} = (A_s^{1/\alpha-1} + A_r^{1/\alpha-1})/T$. Substituting this ω_1 into (28)–(31) implies (16). Then,

$$v_{s,\alpha} = L_s T_{su,\alpha} = T A_s^{1/\alpha}/(A_s^{1/\alpha-1} + A_r^{1/\alpha-1}), \tag{32}$$

$$v_{r,\alpha} = L_r T_{ru,\alpha} = T A_r^{1/\alpha}/(A_s^{1/\alpha-1} + A_r^{1/\alpha-1}). \tag{33}$$

Dividing (32) by (33) yields the first relation in (18). Note that

$$\frac{A_s^{1/\alpha}}{A_s^{1/\alpha-1}+A_r^{1/\alpha-1}} = A_s\frac{A_s^{1/\alpha-1}}{A_s^{1/\alpha-1}+A_r^{1/\alpha-1}} = A_s\left(1-\frac{1}{A_r}\frac{A_r^{1/\alpha}}{A_s^{1/\alpha-1}+A_r^{1/\alpha-1}}\right).$$

This, jointly with (32) and (33), implies the second relation in (18), and the result follows. ■

Proof of Theorem 4: By (21), two cases arise: $A_s > A_r$ and $A_s < A_r$. Let $A_s > A_r$. Then, by (18), (19) and (21), $NP(v_s, v_r) = (v_s - v_\infty)v_r = (TA_s - A_s v_r/A_r - v_\infty)v_r = A_s(TA_s/(A_s+A_r) - v_r/A_r)v_r$. Thus, the $(TA_s - A_s v_\infty/(2A_r), v_\infty/2)$ is the NBS, and the result follows from (19) and the first relation in (18). ■

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