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Multi-Operator Mobile Relaying: Shared-Spectrum Allocation*

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SUMMARY In this paper, we introduce the concept of a multi-operator mobile relay node (RN) for cellular networks on buses or trains. The installation of RNs improves spectral efficiency because an antenna with a higher gain than that of user equipment (UE) can be installed in an RN. However, installing different RNs for different operators is not efficient because of the large amount of space needed to install multiple RNs in a bus. Thus, sharing one RN among multiple operators is a more practical approach. When we use a multi-operator mobile RN, the required amount of resource for each operator varies independently as the RN moves. Consequently, we propose a system of shared-spectrum allocation among operators for RN-UEs communication. Shared bandwidth can be allocated to operators according to link quality in order to achieve effective utilization of radio resources. However, to introduce shared-spectrum allocation, fairness among the operators and the total efficiency of the system should be taken into consideration. Using computer simulations, we evaluate shared-spectrum allocation based on the Nash bargaining solution (NBS). The results, in terms of both fairness and efficiency, indicate that total throughput can be improved by approximately 20% compared with the situation where multiple operators install different RNs individually.

key words: *multi-operator, mobile relaying, scheduling, bargaining game*

1. Introduction

Recently, the 3rd Generation Partnership Project (3GPP) completed standardization of Long Term Evolution-Advanced (LTE-Advanced), the next generation mobile communication system. In the LTE-Advanced system, data rates of up to 1 Gbit/s at 100 MHz bandwidth are supported in downlink.

As part of the process of standardizing further enhancements for LTE-Advanced system, 3GPP has begun discussing the standardization of mobile relaying [1]. It is expected that relay nodes (RNs) will be installed on buses and trains. There are two merits of installing an RN. The first merit is the fact that spectral efficiency is improved because high-gain antennas can be installed in an RN whereas only low-gain antennas can be installed in user equipment (UE). The other merit is that handoff procedures for multiple UEs can be carried out collectively via an RN. This reduces the network load resulting from handoff signals [2].

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However, there may be multiple UEs belonging to different operators on the same bus or train. The easiest way to support the UEs of all the operators is for each operator to install an RN on the bus independently. If multiple operators install different RNs independently, the high infrastructure cost and the lack of space for the installation are problems to be solved.

In the LTE-Advanced system as well, the concept of network sharing has been proposed. This is gaining attention owing to its potential to reduce both infrastructure and environmental costs [3], [4]. Network sharing is the act of multiple operators sharing the same eNodeB (eNB) or spectrum resources. It was introduced as a topic in the 3GPP Release 10 standard [5]. For example, up to six operators are allowed to share the same eNB [6], and network sharing can be applied to various communication systems. The effective use of limited resources by network sharing is expected to become more common [7].

In future, network sharing is expected to be discussed in the area of mobile relay systems as well. In this paper, we propose the installation of multi-operator RNs on buses and trains. By introducing network sharing, the problems of infrastructure costs and lack of installation space can be eliminated. Furthermore, when a mobile RN is installed on a bus, the bandwidth required by each operator for RN-UEs communication varies independently as the spectral efficiency of eNB-RN/UEs communication varies. Thus, flexible resource allocation among the operators can improve the total system efficiency.

In this paper, we propose the introduction of a new shared band for RN-UEs communication and a system of shared-spectrum allocation for multi-operator mobile RNs. The allocated bandwidth for RN-UEs communication can be adjusted as the throughput of eNB-RN varies. This is why the required eNB-RN bandwidth for each operator varies independently as the RN moves. In general, the spectrum allocation for RN-UEs is performed by each operator with their exclusive licensed bandwidth. However, if some parts of the exclusive bandwidth of an operator are unused for the RN-UEs link, spectrum sharing among the operators can be used to improve system performance by effectively allocating the unused bandwidth.

However, there are no rules for the control schemes of such shared systems. This naturally implies that fairness among operators and the total system performance have to be discussed with respect to shared-spectrum allocation when multiple operators share the spectrum resources.

For shared-spectrum allocation where the fairness criteria among operators are satisfied, we introduce the concept of a bargaining game [8]. In the bargaining game, the agreement point for the bargaining problem is discussed when there is a binding contract among the rational players. In particular, Nash bargaining solution (NBS) is known as the solution to the bargaining problem that satisfies the Pareto optimality and the fairness. NBS is an important concept in discussing shared-spectrum allocation problems [9], [10].

In this paper, we propose an NBS-based shared-spectrum allocation framework for multi-operator mobile RNs and evaluate the performance of the system using computer simulations. Furthermore, it is important to evaluate the impact of disagreement point on the agreement point. To the best of our knowledge, this has not been discussed in other research works that apply the theory of bargaining; although there are many research efforts on wireless communications that have reported system improvements using NBS [11].

This paper presents a simple, yet meaningful framework for analyzing the improvement in throughput of the shared-spectrum allocation for multi-operator mobile RNs. The remainder of the paper is organized as follows. In Sect. 2, we introduce multi-operator mobile RNs. In Sect. 3, we describe the concept of bargaining games and NBS, and in Sect. 4 we introduce the shared-spectrum allocation scheme based on NBS. In Sect. 5, we present the results of our simulations and reveal the effect of shared-spectrum allocation on multi-operator mobile RNs. In Sect. 6, we present our conclusions.

2. Multi-Operator Mobile RNs

In this section, we introduce multi-operator mobile RNs that can be installed on a bus, as shown in Fig. 1. For RN-UEs communication, there are two kinds of spectrum usages: using fixed amount of dedicated spectrum licensed to each operator, and shared spectrum among operators. In Sect. 2.1, we discuss these two usage types.

In addition, UEs need not necessarily communicate via the RN. Thus, we consider two choices for each operator: use of only relay transmission, and use of both direct and relay transmission. In Sect. 2.2, the advantages and disadvantages of these two choices are discussed.

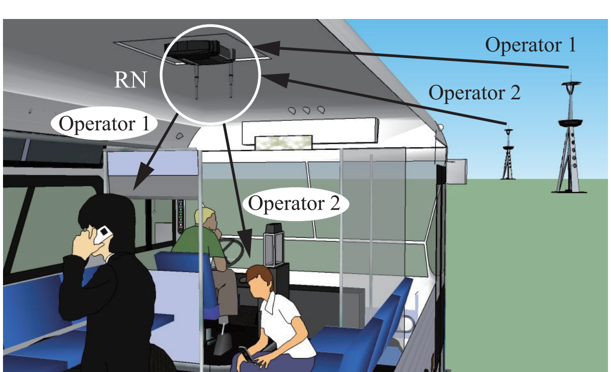


Fig. 1 Multi-operator mobile RN on bus.

2.1 Spectrum Usage of RN-UEs Communication

2.1.1 Fixed Amount of Dedicated Spectrum

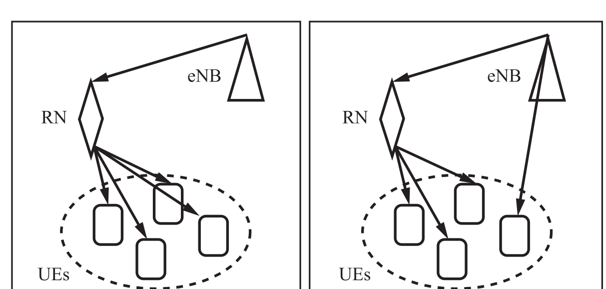
One of the simplest ways to facilitate communication between an RN and UEs is to use exclusive licensed bands for each operator. One advantage of this usage is that each operator can allocate their own bandwidth exclusively, without taking into account the spectrum allocation of the other operators. However, in this scenario, if a part of the bandwidth is unused by one operator, it cannot be used by the other operators, which is inefficient from the viewpoint of the total throughput.

2.1.2 Shared Spectrum

Sharing the spectrum among all operators is another method of RN-UEs communication. When the bandwidth allocated for RN-UEs is adjusted according to the link quality of eNB-RN, the total throughput is improved compared with the situation in which a fixed amount of dedicated spectrum is used. This is because the link quality of eNB-RN for each operator varies independently as the bus moves, and the bandwidth required by each operator for RN-UEs communication also varies. On the other hand, there is a disadvantage in that the operators need to establish a rule that satisfies the fairness criteria among the operators while achieving high total throughput. In addition, when the allocated bandwidth for RN-UEs is determined at the RN, the complexity of the signalling scheme increases because appropriate control signals for spectrum allocation of the other links are needed in order to maximize system throughput.

2.2 Availability of Direct Communication

When all data are transmitted via an RN as illustrated in Fig. 2(a), the end-to-end throughput is limited by the link with the lowest capacity, which is a bottleneck in end-to-end communications. However, if the capacity of RN-UEs



(a) Relay only. (b) Relay and direct.

Fig. 2 Availability of direct communication.

is lower than that of eNB-RN, both eNB-UEs direct transmission and eNB-RN-UEs relay transmission as shown in Fig. 2(b), and spectrum allocation can be used to solve the bottleneck problem.

3. Bargaining Game

In this section, the concept of bargaining game is introduced [8], [12]. An N-person bargaining problem consists of a pair $(\mathcal{U}, \boldsymbol{X})$, where $\mathcal{U}$ is a convex subset of $\mathcal{U} \subset \mathbb{R}^N$ and a vector of utilities $\boldsymbol{X} = (X_1, \ldots, X_N)$. $\mathcal{U}$ is the subset of the feasibly expected utilities that all players can collectively achieve, and X_i is the utility of player $i \in \{1, \ldots, N\}$ when they fail to reach an agreement.

In the bargaining game, the vector of utilities at the agreement point $\boldsymbol{\eta} = (\eta_1, \ldots, \eta_N)$ over the bargaining problem $(\mathcal{U}, \boldsymbol{X})$ is chosen on the Pareto frontier. The Pareto frontier is the area where no player can improve the utility without reducing the utility of the other players.

NBS is a well-known solution to the bargaining problem. It is defined as

$$\boldsymbol{\eta} = \arg\max_{\boldsymbol{x} \in \mathcal{U}} \prod_{i=1}^{N} (x_i - X_i), \tag{1}$$

where $\boldsymbol{x} = (x_1, \ldots, x_N)$ represents a vector of utilities. NBS satisfies not only the Pareto optimality but also the fairness among the players. When $\boldsymbol{X} = (0, \ldots, 0)$, the above definition is equivalent to that of the proportional fairness [13].

4. Shared-Spectrum Allocation Based on NBS

In this section, we describe shared-spectrum allocation based on NBS. The shared-spectrum allocation computation rules for RN-UEs communication should satisfy both Pareto optimality and fairness among operators. The computation rules can be discussed using the bargaining game concept and NBS. The spectrum allocation enabling communication over all links can be performed by computing the NBS over the bargaining game.

In the following, a two-operator mobile RN is considered. Let the eNB of operator $i\,(\in \{1, 2\})$ be denoted by eNB$^{(i)}$, and let the UEs of operator i be denoted by UEs$^{(i)}$.

Note that the discussion below can be extended to a general N-operator mobile RN because bargaining problems among more than two players can also be formulated as a bargaining game [12]. When only a part of the operators can improve their throughput, the product of improved throughput of all operators is 0 and NBS cannot be calculated. In such a case, shared-spectrum allocation problem can be regarded as a bargaining game among only the operators which can improve their throughput and the NBS can be calculated appropriately.

4.1 System Model

Figures 3 and 4 show the assumptions made on the spectrum that each operator can use. Note that since eNBs are

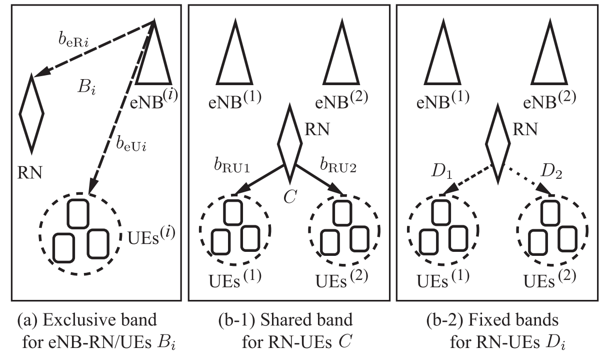


Fig. 3 Available spectrum in each link.

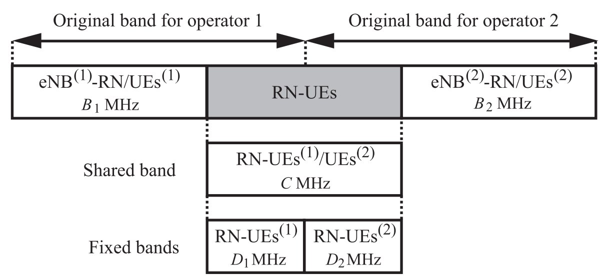


Fig. 4 Licensed spectrum for each operator.

assumed to have already been developed, they can use a dedicated bandwidth for each operator, while the shared RN should transmit at frequencies of both operators.

As shown in Fig. 3(a), operator i is assumed to use dedicated bandwidth B_i MHz for eNB-RN links and eNB-UEs links. Let the allocated orthogonal bandwidth for eNB$^{(i)}$-RN be denoted by $b_{\mathrm{eR}i}$ and that for eNB$^{(i)}$-UEs$^{(i)}$ be denoted by $b_{\mathrm{eU}i}$. They should satisfy $b_{\mathrm{eR}i} + b_{\mathrm{eU}i} \leq B_i$.

We then assume additional bandwidth C MHz for RN-UEs communication. Note that we can assume that dedicated bandwidth B_i is reused for RN-UEs communication; however, for the sake of a simple analysis, we assumed additional bandwidth.

When the shared spectrum is used for RN-UEs communication, the additional bandwidth of C is shared between the operators, as shown in Fig. 3(b-1). Here, $b_{\mathrm{RU1}} + b_{\mathrm{RU2}} \leq C$ where $b_{\mathrm{RU}i}$ denotes the allocated bandwidth for RN-UEs$^{(i)}$. On the other hand, when a fixed amount of dedicated spectrum is used, D_i MHz is assumed to be used by operator i as shown in Fig. 3(b-2). Here, the allocated bandwidth for RN-UEs$^{(i)}$ should satisfy $b_{\mathrm{RU}i} \leq D_i$.

4.2 Scheduling Based on NBS

Setting the agreement point is the scheduling problem for the shared spectrum. This problem can be solved by the computing NBS in the bargaining game.

In Sect. 3, NBS is described as the point where the product of the excess utilities is maximized. We now consider the case where shared spectrum is allocated to each operator as the product of the excess throughput above the disagreement point (T_1, T_2) is maximized, where T_i denotes the throughput of operator i at the disagreement point.

Shared-spectrum allocation is formulated as (2) where $x_i(\boldsymbol{b})$ is the throughput of operator i and (t_1, t_2) is given by the NBS:

$$(t_1 - T_1)(t_2 - T_2) = \max_{\boldsymbol{b}} (x_1(\boldsymbol{b}) - T_1)(x_2(\boldsymbol{b}) - T_2), \quad (2)$$

$$x_i(\boldsymbol{b}) = \eta_{\mathrm{eU}i} b_{\mathrm{eU}i} + \min\{\eta_{\mathrm{eR}i} b_{\mathrm{eR}i}, \eta_{\mathrm{RU}i} b_{\mathrm{RU}i}\}, \quad (3)$$

where $\eta_{\mathrm{eU}i}$, $\eta_{\mathrm{eR}i}$, and $\eta_{\mathrm{RU}i}$ represent the spectral efficiency of eNB$^{(i)}$-UEs$^{(i)}$ links, eNB$^{(i)}$-RN links, and RN-UEs$^{(i)}$ links, respectively. Note that $\boldsymbol{b}$ represents the vector of the allocated bandwidth for all links as

$$\boldsymbol{b} = (b_{\mathrm{eU1}}, b_{\mathrm{eR1}}, b_{\mathrm{eU2}}, b_{\mathrm{eR2}}, b_{\mathrm{RU1}}, b_{\mathrm{RU2}}), \quad (4)$$

$$b_{\mathrm{eU}i} + b_{\mathrm{eR}i} \le B_i, \; b_{\mathrm{RU1}} + b_{\mathrm{RU2}} \le C. \quad (5)$$

The first term of (3) represents the throughput of the direct transmission from eNB to UEs. The second term represents the throughput of relay transmission via the RN. Here, let $\boldsymbol{b}^\star$ denote the optimal solution of (2).

Note that NBS can be defined only when the throughput of both operators can be improved simultaneously. In the assumed spectrum sharing system, there is a possibility that only one of the operators can improve the throughput performance. In such a case, we cannot analyze this resource allocation problem by using the bargaining game and NBS. However, even in such a case, there is only one point where none of the two operators can improve the throughput without reducing that of the other operator. Thus, this point is chosen as the agreement point.

4.3 Disagreement Point

If the negotiation breaks down, the combined utilities of both operators reaches the point that is achieved by each operator without cooperation. The utilities at the disagreement point depend on whether each operator attempts to install the RN independently.

If operator i does not attempt to install the RN without cooperation and uses only eNB-UEs communication, B_i will be allocated only to eNB$^{(i)}$-UEs$^{(i)}$ links, and thus we get

$$T_i = \eta_{\mathrm{eU}i} B_i. \quad (6)$$

On the other hand, if operator i installs the RN using a fixed amount of dedicated band B_i for RN-UEs communication, the throughput performance of the system is assumed to be the same as that using a fixed amount of dedicated spectrum, and thus we get

$$T_i = \max_{b_{\mathrm{eU}i}, b_{\mathrm{eR}i}, b_{\mathrm{RU}i}} \{\eta_{\mathrm{eU}i} b_{\mathrm{eU}i} + \min\{\eta_{\mathrm{eR}i} b_{\mathrm{eR}i}, \eta_{\mathrm{RU}i} b_{\mathrm{RU}i}\}\}, \quad (7)$$

$$b_{\mathrm{eU}i} + b_{\mathrm{eR}i} \le B_i, \; b_{\mathrm{RU}i} \le D_i. \quad (8)$$

Since two operators are assumed herein, the following four disagreement points are possible;

(a) Both operators: Both operators install the RNs independently. The expression for T_i for both operator is as given in (7).

(b) Only operator 1: Only operator 1 installs the RN. The expression for T_1 is as given in (7) and that for T_2 is as given in (6).

(c) Only operator 2: Only operator 2 installs the RN. The expression for T_1 is as given in (6) and that for T_2 is as given in (7).

(d) No operator: Neither operator installs the RN. The expression for T_i for both operator is as given in (6).

4.4 Impact of Bandwidth on Feasible Utilities and Disagreement Point

We would like to point out that regardless of the values of B_i, C, and D_i, the product of the excess utilities of shared-spectrum allocation is greater than or equal to that of fixed amount of dedicated spectrum scheme. In addition, as a result, the total throughput performance is also improved by using shared-spectrum allocation. The reason is as follows. When we use different values for B_i, C, and D_i, only the set of feasible utilities and the disagreement point are changed in the bargaining game. This is because the set of feasible utilities is formulated by (3)–(5), (8) and the utilities of a disagreement point is formulated by (6)–(8). Regardless of B_i, C, and D_i, the disagreement point is an element of the set of the feasibly expected utilities by using fixed amount of dedicated spectrum scheme. This is because the utilities which are gotten by (6)–(8) are special cases of the conditions (3), (8). Furthermore, the set of feasibly expected utilities by using fixed amount of dedicated spectrum scheme is the subset of the set by using shared-spectrum allocation because the degree of freedom of fixed amount of dedicated spectrum scheme is less than that of shared-spectrum allocation.

4.5 Signalling

The eNBs are not directly connected to each other and thus cannot directly exchange the information needed for shared-spectrum allocation. In order to calculate the NBS and the appropriate resource allocation, information about $\eta_{\mathrm{eU}i}$, $\eta_{\mathrm{eR}i}$, and $\eta_{\mathrm{RU}i}$ should be collected at the RN. Originally, eNB$^{(i)}$ has the information of $\eta_{\mathrm{eU}i}$ and $\eta_{\mathrm{eR}i}$, and the RN has the information about $\eta_{\mathrm{RU}i}, \forall i$. By sending information on $\eta_{\mathrm{eU}i}$ and $\eta_{\mathrm{eR}i}$ from the eNBs to the RN, the RN can obtain the all the information needed and it calculate the appropriate resource allocation $\boldsymbol{b}^\star$ as (2). Finally, the RN informs the eNBs about $\boldsymbol{b}^\star$.

5. Performance Evaluations

In this section, we evaluate and compare the throughput of the fixed amount of dedicated spectrum scheme and that of the shared spectrum scheme. In the performance evaluation, B_i, C, and D_i are set to 20 MHz, 20 MHz, and 10 MHz, respectively. Note that maximum 20 MHz component carrier is supported in the LTE-Advanced systems.

In all performance evaluations in this section, for the sake of simplicity, let us assume that the information about the spectral efficiency of all the links, i.e., η_{eU1}, η_{eR1}, η_{eU2}, η_{eR2}, η_{RU1}, and η_{RU2}, are known when searching for the optimal solution $\boldsymbol{b}^\star$ to the optimization problem (2).

5.1 Performance Evaluations

In section from 5.1 to 5.4, the total throughput $t_1 + t_2$ against η_{eR2} (≤ 4.19 bit/s/Hz) is calculated for each scheme, where η_{eR1} is set to 1 bit/s/Hz, 2.5 bit/s/Hz, or 4 bit/s/Hz. The distances from the RN to the UEs are assumed to be short enough, and thus we set $\eta_{\mathrm{RU}i} = 4.19$ bit/s/Hz.

In this evaluation, using only one-layer communication is considered. From one-layer transport block size (TBS) table presented in [14], when TBS index is 26 and the number of physical resource blocks (PRBs) is 73, 55056 bit are allocated to 73 PRBs. In this case, we can get the maximal spectrum efficiency with 64QAM as follows:

$$\frac{55056\,\mathrm{bit}}{73\,\mathrm{PRB} \times 180\,\mathrm{kHz} \times 1\,\mathrm{ms}} = 4.19\,\mathrm{bit/s/Hz}, \tag{9}$$

where 1 PRB is defined as 180 kHz × 1 ms. Fot this reason we assume the maximal spectrum efficiency of all links is set to $\eta_{\max} = 4.19$ bit/s/Hz.

In order to calculate the throughput of eNB-UEs communication, $\eta_{\mathrm{eU}i}$ is obtained using the value of $\eta_{\mathrm{eR}i}$ and the following equations:

$$\eta_{\mathrm{eU}i} = \log_2(1 + \gamma_{\mathrm{eU}i}), \tag{10}$$

$$10\log_{10}\gamma_{\mathrm{eR}i} - 10\log_{10}\gamma_{\mathrm{eU}i} = G_{\mathrm{RN}} - G_{\mathrm{UEs}} - F_{\mathrm{RN}} + F_{\mathrm{UEs}}, \tag{11}$$

$$\eta_{\mathrm{eR}i} = \log_2(1 + \gamma_{\mathrm{eR}i}), \tag{12}$$

where $\gamma_{\mathrm{eR}i}$ and $\gamma_{\mathrm{eU}i}$ represent the SNR of each link. Let us assume that the antenna gain of the RN $G_{\mathrm{RN}} = 7$ dBi and that of the UEs $G_{\mathrm{UEs}} = 0$ dBi. The noise figure of RN $F_{\mathrm{RN}} = 7$ dB and that of the UEs $F_{\mathrm{UEs}} = 9$ dB as described in [15], [16]. The spectrum efficiency of all links are assumed to be the same as the channel capacity and the channel gain of eNB-RN and that of eNB-UEs links are set to the same. This is why the difference of the received signal to noise power ratio (SNR) $10\log_{10}\gamma_{\mathrm{eR}i} - 10\log_{10}\gamma_{\mathrm{eU}i}$ can be represented as (11).

5.2 Total Throughput

Figure 5 shows the total throughput $t_1 + t_2$ of the fixed amount of dedicated spectrum scheme, that of the shared spectrum scheme, and that at the disagreement point $T_1 + T_2$ in case (d) discussed in Sect. 4.3. In case (d), neither operator installs RNs individually at the disagreement point and T_i of both operators is calculated as (6).

In the case where $\eta_{\mathrm{eR1}} = 2.5$ bit/s/Hz and 4 bit/s/Hz, the total throughput is improved by about 20% when η_{eR2} is less than 2.1 bit/s/Hz. Similarly, in the case where $\eta_{\mathrm{eR1}} = 1$ bit/s/Hz, the total throughput is improved when η_{eR2} is greater than 2.1 bit/s/Hz. This is because unused

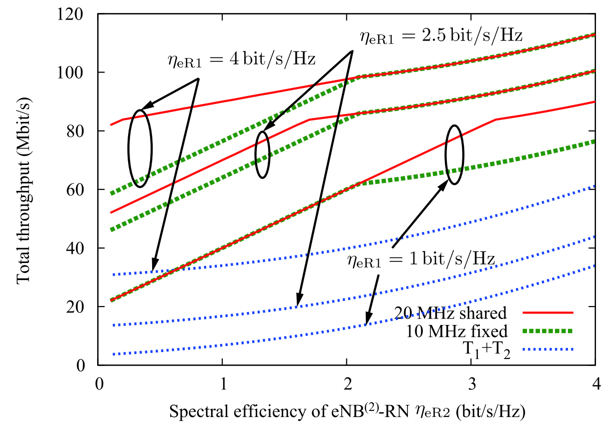


Fig. 5 Total throughput of shared-spectrum allocation.

spectrum is reduced when the shared spectrum scheme is used, in comparison to the fixed amount of dedicated spectrum scheme. However, the total throughput is not improved when η_{eR2} is greater than 2.1 bit/s/Hz where $\eta_{\mathrm{eR1}} = 4$ bit/s/Hz or 2.5 bit/s/Hz. This is because both operators use all of their bandwidth for the RN-UEs communication even when the fixed amount of dedicated spectrum scheme is used.

The total throughput is not improved in the case where $\eta_{\mathrm{eR1}} = 1$ bit/s/Hz when η_{eR2} is less than 2.1 bit/s/Hz. This is because both of the operators can allocate enough bandwidth for RN-UEs compared with the bandwidth for eNB-RN even when the fixed amount of dedicated spectrum scheme is used.

In addition, we can see a different trend of the throughput improvement between cases $\eta_{\mathrm{eR}i} > 2.1$ bit/s/Hz and $\eta_{\mathrm{eR}i} < 2.1$ bit/s/Hz. This is because throughput is determined by (3) and smaller value of $\eta_{\mathrm{eR}i} b_{\mathrm{eR}i}$ and $\eta_{\mathrm{RU}i} b_{\mathrm{RU}i}$ in (3) is varied around $\eta_{\mathrm{eR}i} = 2.1$ bit/s/Hz. When $\eta_{\mathrm{eR}i} > 2.1$ bit/s/Hz, if operator i allocates 20 MHz to eNB$^{(i)}$-RN link, the end-to-end throughput of the relay transmission is limited because only 10 MHz can be allocated to RN-UEs$^{(i)}$ communication. In such a case, operator i allocates only a part of 20 MHz to eNB$^{(i)}$-RN link and the other part to eNB$^{(i)}$-UEs$^{(i)}$ link. On the other hand, when $\eta_{\mathrm{eR}i} < 2.1$ bit/s/Hz, even if 20 MHz is allocated to eNB$^{(i)}$-RN link, operator i need not to allocate more than or equal to 10 MHz bandwidth to RN-UEs$^{(i)}$ link. Note that shared-spectrum allocation improves the total throughput performance, because the allocated bandwidth of eNB-UEs transmission is reduced by flexible resource allocation for RN-UEs communication.

5.3 Allocated Bandwidth

The shared bandwidth allocated for operator 1 is shown in Fig. 6. In the case where $\eta_{\mathrm{eR1}} = 1$ bit/s/Hz, the allocated bandwidth b_{RU1} has a constant value regardless of η_{eR2}. In addition, in the case where $\eta_{\mathrm{eR1}} = 2.5$ bit/s/Hz and 4 bit/s/Hz, more than 10 MHz of bandwidth is allocated for

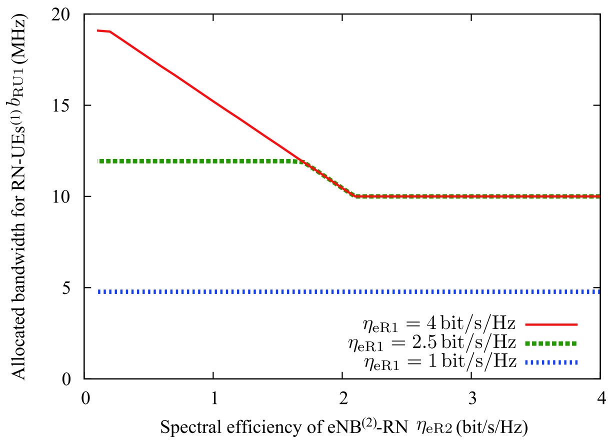


Fig. 6 Allocated bandwidth for RN-UEs$^{(1)}$, b_{RU1}.

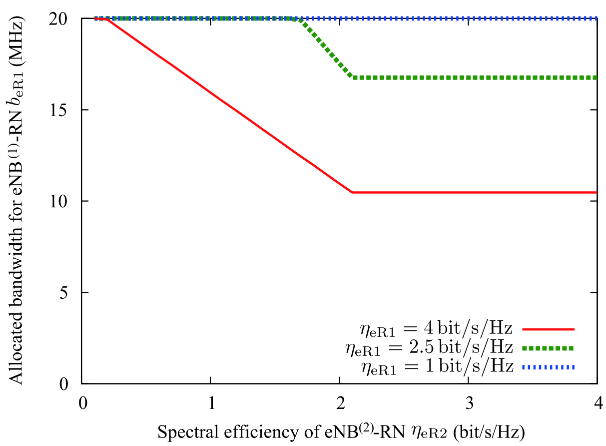


Fig. 7 Allocated bandwidth for eNB$^{(1)}$-RN, b_{eR1}.

RN-UEs$^{(1)}$ regardless of η_{eR2}.

Figure 7 shows the bandwidth allocated for eNB$^{(1)}$-RN. The appropriate bandwidth for the eNB-RN of each operator can be calculated according to the allocated shared bandwidth. In the case where η_{eR1} = 1 bit/s/Hz, 20 MHz of bandwidth is allocated to eNB$^{(1)}$-RN regardless of η_{eR2}. In the case where η_{eR1} = 2.5 bit/s/Hz and 4 bit/s/Hz, a part of B_1 is allocated to the eNB$^{(1)}$-RN link and the remaining part is allocated to the eNB$^{(1)}$-UEs$^{(1)}$ link. Compared with the fixed amount of dedicated spectrum scheme, more bandwidth b_{eR1} is allocated for the relay communication, which is hence effectively used.

5.4 Comparison of Four Disagreement Points

As presented in Sect. 4.3, four types of disagreement points can be considered when the negotiation breaks down. In this section, the total throughput performance is compared among four disagreement points.

Figure 8 shows the performance in terms of total throughput of shared-spectrum allocation for four different disagreement points. Note in this figure, the performance of “(d) No operator” is the same as the performance as shown in Fig. 5.

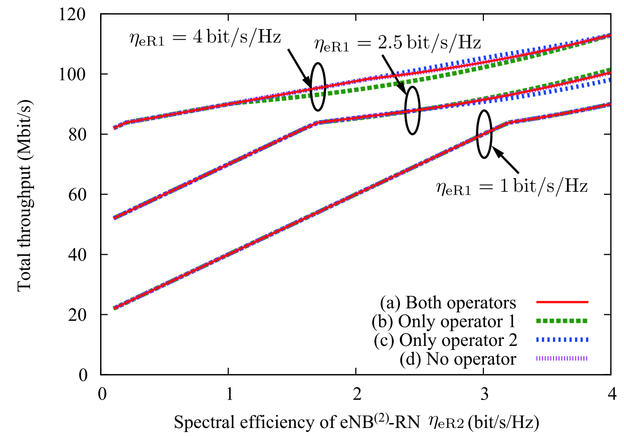


Fig. 8 Total throughput of shared-spectrum allocation depending on four disagreement points.

As shown in Fig. 8, when both η_{eR1} or η_{eR2} are small, the total throughput of “(a) Both operators”, that of “(b) Only operator 1”, and that of “(c) Only operator 2” are the same as that of “(d) No operator”. This is because when the throughput at the disagreement point is low, there is a small impact of the difference of the disagreement point on the NBS throughput performance.

On the other hand, when η_{eR1} and η_{eR2} are large, the total throughput performance of these disagreement points are different from that of “(d) No operator”. For example, the total throughput of “(b) Only operator 1” with η_{eR1} = 4 bit/s/Hz is degraded, as compared to that of “(d) No operator”. At the disagreement point, 10 MHz band is already allocated to RN-UEs$^{(1)}$ communication and no band is allocated to RN-UEs$^{(2)}$ communication. This is why more than 10 MHz band should be allocated to operator 1 in order to improve the throughput performance of both operators fairly. However, only less than 10 MHz band is allocated to operator 2 at the NBS and throughput improvement of operator 2 is limited. Similarly, we can see the total throughput of “(c) Only operator 2” with η_{eR1} = 2.5 bit/s/Hz and η_{eR2} = 4 bit/s/Hz is degraded as compared to that of “(d) No operator”.

From Fig. 8, it can be seen that the total throughput differs according to the disagreement point, however, the difference in the total throughput is negligible. For example, when η_{eR1} = 4 bit/s/Hz, the difference in the total throughput is less than 5%. Note that irrespective of the location of the disagreement point, the total throughput by shared-spectrum allocation can be improved.

5.5 Total Throughput in Path Loss Models

The total throughput performance of shared-spectrum allocation when both operators do not install RNs individually at the disagreement point is evaluated by considering the path loss models of LTE [15] to clarify the impact of the position of RN on the performance. As shown in Fig. 9, the RN is located between eNB$^{(1)}$ and eNB$^{(2)}$, and the distance between them is set to 4.0 km. The total throughput is eval-

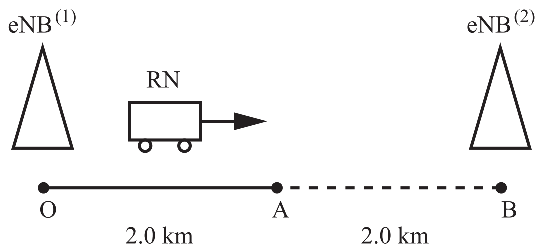


Fig. 9 Simulation model.

Table 1 Simulation parameters [15], [16].

Transmitter power density	eNB	28, 33, 38 dBm/20 MHz
	RN	23 dBm/20 MHz
Antenna gain	eNB	14 dBi
	RN (eNB-RN link)	7 dBi
	RN (RN-UEs link)	5 dBi
	UEs	0 dBi
path loss model (dB)	eNB-RN	$125.2 + 36.3 \log_{10}(R/\mathrm{km})$
	eNB-UE	$131.1 + 42.8 \log_{10}(R/\mathrm{km})$
	RN-UE	$128.1 + 37.6 \log_{10}(R/\mathrm{km})$
Noise figure	RN	7 dB
	UEs	9 dB

uated for an RN located on the straight-line segment OA at three transmitter power density levels of eNBs: 28 dBm, 33 dBm, and 38 dBm for 20 MHz bandwidth.

Table 1 summarizes the simulation parameters. In this evaluation, 2 GHz band is assumed to be used in every link. The parameters of path loss models are set as described in [15]. The transmitter power density, antenna gain, and noise figure of the RN are also set as presented in [15]. These parameters of the eNB and UEs are set as presented in [16]. Note that the transmitter power density of the eNBs are set to less than the maximal value in LTE standerd, 49 dBm/20 MHz. In addition, the distance between the RN and the UEs is set to 10 m and the maximal spectral efficiency of all links are set to 4.19 bit/s/Hz as discussed in Sect. 5.1.

In this evaluation, we estimate spectral efficiency of each link by the calculation of the channel capacity. For example, eNB$^{(i)}$-RN link $\eta_{\mathrm{eR}i}$ is calculated as follows:

$$\eta_{\mathrm{eR}i} = \min\{\log_2(1+\gamma_{\mathrm{RN}i}), \eta_{\max}\}, \tag{13}$$

$$10\log_{10}\gamma_{\mathrm{RN}i} = P_{\mathrm{eNB}i} + G_{\mathrm{eNB}i} + G_{\mathrm{RN}i} - L_{\mathrm{eR}i} - F_{\mathrm{RN}} - P_{\mathrm{n}}\ (\mathrm{dB}), \tag{14}$$

where $P_{\mathrm{eNB}i}$ represents the transmitter power density of eNB$^{(i)}$, $L_{\mathrm{eR}i}$ represents the path loss of the eNB$^{(i)}$-RN links, and P_n represents the thermal noise power density which is -114 dBm/MHz. The spectral efficiency of other links $\eta_{\mathrm{eU}i}$ and $\eta_{\mathrm{RU}i}$ are also calculated in the same way.

The simulation results are shown in Fig. 10. When the transmitter power density is 28 dBm/20 MHz, the total throughput is improved by shared-spectrum allocation. When the link quality of eNB-RN differs between operators, appropriate spectrum allocation enables the effective utilization of radio resources.

However, when the transmitter power density is 33 dBm/20 MHz, the total throughput does not improve. This is because the bandwidth for RN-UEs communication is almost completely used regardless of whether fixed or shared spectrum schemes are used.

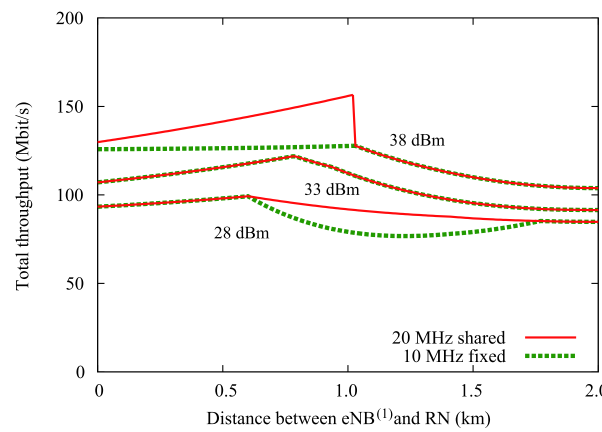


Fig. 10 Total throughput for the distance between eNB$^{(1)}$ and RN.

When the transmitter power density is 38 dBm/20 MHz, shared-spectrum allocation improves the total throughput performance. However, the improvement of total throughput due to shared-spectrum allocation is achieved only when the distance between eNB$^{(1)}$ and RN is smaller than 1 km. This is because the RN is close to eNB$^{(1)}$, and operator 1 can achieve the same throughput irrespective of whether transmitting via the RN or not. This results in operator 1 allocating its exclusive 20 MHz spectrum solely to eNB$^{(1)}$-UEs$^{(1)}$, and the shared 20 MHz bandwidth can only be allocated to RN-UEs$^{(2)}$.

As shown in Fig. 10, when the distance between eNB$^{(1)}$ and RN is larger than 1 km, the total throughput performance is dramatically degraded. This is because when $\eta_{\mathrm{eR}1}$ is larger than $\eta_{\mathrm{eU}1}$, operator 1 should transmit data via the RN in order to improve the throughput of both operators fairly. This results in that the shared spectrum is allocated to not only RN-UEs$^{(2)}$ but also RN-UEs$^{(1)}$, and the throughput of operator 2 is dramatically degraded. In this case, 10 MHz bandwidth is allocated to both operators no matter whether the RN-UEs spectrum is shared or not.

6. Conclusion

In this paper, we proposed the multi-operator mobile RN concept and discussed the advantages of a system of shared-spectrum allocation for RN-UEs communication among different operators. From the results of performance evaluations, the proposed NBS-based shared-spectrum allocation was found to enable an improvement in the total throughput of approximately 20% compared with a non-shared mobile RN.

We would like to emphasize that the purpose of this paper was to reveal the effect of the shared-spectrum allocation for multi-operator RN. We hope that the results presented in this paper will provide insights that are useful in the design of mobile relaying systems.

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