Demand-Based Radio Resource Allocation for Device-to-Device Communications: A Game Approach

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Abstract. With the proliferation of the number of mobile devices, it is urgent to develop new technologies to cope with the rapidly growing volume of mobile data. Device-to-device (D2D) communication has been considered as one of the key technologies to solve this problem. In this paper, under the premise that D2D pairs share the uplink spectrum of cellular user (CU), a radio resource allocation scheme is proposed to allocate resource blocks (RBs) to D2D pairs while the co-channel interference threshold of CU is met. The D2D pairs whose total number of demanded RBs falls within a predefined range are organized into a coalition. Based on the total number of demanded RBs, the proposed scheme first allocates RBs to each coalition. Then, in each coalition, the Nash Bargaining Solution (NBS) is used to further allocate RBs to the belonging D2D pairs. The simulation results show that the reuse ratio of the Reusable RBs is nearly 100%. In addition, when the required number of RBs is greater than that can be allocated, the proposed scheme proportionally allocates RBs to all D2D pairs.

Keywords: D2D communication · Radio resource allocation · Coalition Nash Bargaining Solution

1 Introduction

In response to the rapid growth of the amount of mobile data, device-to-device (D2D) communication technology has been considered as one of the possible solutions. In addition to reducing the loading of evolved NodeB (eNB) and enhancing the overall system capacity, D2D communications also greatly reduce the data transmission delay due to the short distance between two D2D devices. However, since D2D communication technology is not fully mature yet, there are still many issues that need to be further explored, such as radio resource allocation, power control, device discovery, and D2D mode selection. Among them, many of the literature addressed to the radio resource allocation problem. One of the possible solutions to this problem is to improve the spectrum efficiency. To improve the spectrum efficiency, one of the alternatives is the D2D communications share the uplink spectrum used by the Cellular Users (CUs).

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This approach is also regarded as the inband underlay [1]. However, due to the co-channel interference problems, it is necessary to design a radio resource allocation scheme [2] to appropriately allocate resource blocks (RBs) to D2D pairs so that the interference to CUs can be maintained in an acceptable level. To this problem, most of the literatures aimed to maximize the overall system transmission rate. However, the requested transmission rate by each D2D pair is not considered. Therefore, this paper attempts to design a resource allocation scheme that takes user requirements in terms of the number of demanded RBs into consideration.

The rest of this paper is organized as follows. Section 2 briefly introduces the fundamental concepts used in this paper. Section 3 describes the proposed demand-based radio resource allocation scheme. The simulation results and discussions are in Sect. 4. Section 5 concludes this paper.

2 Preliminaries

D2D communication was first defined in 3GPP Release 12. The core concept of D2D communication is to allow two closely spaced devices to communicate directly without going through the eNB. The application scenario of D2D communication is very extensive. For example, within the small area, D2D pairs can share multimedia directly. In such a way, not only the transmission delay is reduced, the loading of eNB is offloaded as well [3]. One of the most critical issues for the D2D communication to be applicable is how D2D pairs share the radio spectrum with the existing CUs so that the overall spectrum utilization is increased. Hence, it is important to study how to allocate the radio resources to the D2D pairs under the premise of the interferences to the CUs are tolerable.

A brief literature review is given below. In [4], to achieve the fairness, maximize the entire system rate, and simplify the complexity of radio resource allocation in the OFDMA networks, a two-user bargaining algorithm was proposed based on the concept of Nash Bargaining Solution (NBS) [5] to fairly allocate the subcarriers when the number of mobile user is two. In case of the number of mobile users is more than two, the Hungarian algorithm was used to optimally select two mobile users to form a coalition [6, 7]. In such a way, the two-user bargaining algorithm can be applied to each coalition. With this approach, the number of combinations to allocate radio resources is greatly reduced. In contrast to be applied to the OFDMA system, the authors in [8] applied the concepts of coalition and NBS to the LTE system. Similar to [4], the coalitions in [8] are also formed with equal size while the coalition size can be more than two. All possible sizes of coalitions are generated. Unlike the subcarriers are allocated individually in [4], a fixed number of continuous subcarriers are organized into group to reduce the allocation complexity. Furthermore, to achieve the fairness, the same number of subcarrier groups are allocated to coalitions with the same size. After the subcarrier groups are allocated to all possible sizes of coalitions, the final coalition size is selected by only testing the sum rate achieved by the sampled coalition sizes.

Obviously, in order to deal with the multiuser scenarios, the use of the Hungarian algorithm in [4] greatly increases the computational complexity. Although the coalition size in [8] can be more than two, it is required to be fixed and equal among coalitions. Furthermore, to achieve the fairness, equal number of subcarriers are allocated to coalitions with the same size. However, by viewing the above approaches, the data rate requirements of the mobile users are not considered not only in coalition formation but also in RB allocation. In the application scenarios of D2D communications, we believe that it is important to meet the diverse requirements of the D2D pairs.

Unlike to limit the size of coalition, we proposed a coalition formation method that groups D2D pairs into coalition based on the number of demanded RBs. After the coalition formation, if needed, NBS is used to further allocate the allocated RBs to D2D pairs inside a coalition. Based on the proposed radio resource allocation scheme, the limited uplink radio resources can be utilized more effectively.

3 Demand-Based Radio Resource Allocation

As the system model depicted in Fig. 1, we assumed there are N_C CUs and N_{D2D} D2D pairs within the coverage area of an eNB. An eNB allocates the uplink RBs to CUs based on the semi-persistent scheduling mechanism. Besides, all D2D pairs are assumed to share the uplink RBs of CUs. After receiving the demanded data rate of D2D pair i, we assumed eNB converts it into the number of demanded RBs. In such a way, $N_i^{RB,req}$ is used to represent the number of RBs requested by D2D pair i and is assumed uniformly distributed over $[\alpha_{\min}, \alpha_{\max}]$. $\mathbf{C}_q$ is the set of D2D pairs in the q^{th} coalition. We also assumed that eNB knows the locations of D2D pairs.

The SINR of D2D pair i in coalition q that reuses the uplink RBs of CU j is given by

$$SINR_{i,j}^q = \frac{P_i G_{i,i}}{P_j G_{j,i} + N}, \tag{1}$$

where P_i is the transmission power of D2D pair i, $G_{i,i}$ is the channel gain between the receiver and the transmitter of the D2D pair i, P_j is the transmission power of CU j, $G_{j,i}$ is the channel gain between CU j and one of the two devices of D2D pair i that nearest to CU j, and N is the thermal noise.

Given D2D pair i in coalition q is allocated $N_i^{RB,allocated}$ RBs, the capacity is obtained by

$$R_{q,i} = 180 \times N_i^{RB,allocated} \times \log_2(1 + SINR_{i,j}^q). \quad \text{(Kbps)} \tag{2}$$

Next, we will explain how to form a coalition. As mentioned earlier, the number of demanded RBs of a D2D pair is considered as the criterion for forming coalition. In particular, when a coalition $\mathbf{C}_q$ (excluding the last formed coalition), the aggregated

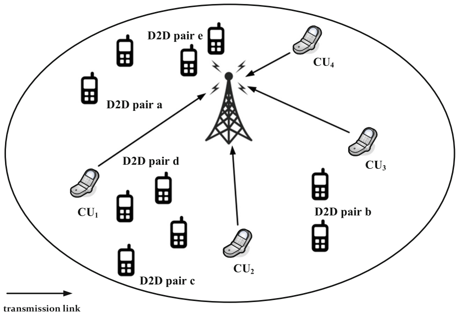

Fig. 1. System model

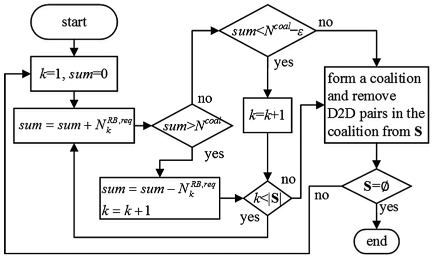

Fig. 2. Flow chart for coalition formation.

number of demanded RBs for all D2D pairs in the coalition $N_{q,total}^{RB,req} = \sum_{i \in C_q} N_i^{RB,req}$ is bounded by

$$N^{coal} - \varepsilon \leq N_{q,total}^{RB,req} \leq N^{coal}, \tag{3}$$

where N^{coal} is the maximum aggregated number of demanded RBs in a coalition and ε is a tolerance value. Both of them are system parameters. As to the last formed coalition, the total number of demanded RBs is allowed to be less than $N^{coal} - \varepsilon$. The flow chart for coalition formation is depicted in Fig. 2. In this flow chart, k is an index of D2D pair, *sum* is the up-to-date aggregated number of demanded RBs, and **S** is a set of D2D pairs in which D2D pairs are listed based on the descending order of the number of demanded RBs. For example, by employing the coalition formation flow chart in Fig. 2 to the example network as shown in Fig. 3, **S** = {**a**, **b**, **c**, **e**, **d**} and three coalitions, $\mathbf{C}_1$ = {**a**}, $\mathbf{C}_2$ = {**b**, **c**}, and $\mathbf{C}_3$ = {**e**, **d**}, are generated if $N^{coal} = 4$ and ε = 1.

Since D2D pairs are assumed to use the uplink RBs of CUs, it is necessary to properly allocate RBs to D2D pairs so that the interference to CUs below a tolerable threshold. To achieve this, first, if the SNR of a RB used by CU perceived at the eNB is higher than a threshold $SNR_{th}^{RB,CU}$, this RB is eligible to be shared to D2D pairs and is referred as a Reusable RB. In addition, if a RB whose SINR perceived at the receiver of a D2D pair is higher than $SINR_{th}^{RB,D2D}$, it is regarded as a Preferred RB by this D2D pair. After receiving the Preferred RBs reported from a D2D pair, the Available RBs, RBs that are available to this D2D pair, of this D2D pair are determined at the eNB by finding the intersection among Reusable RBs and Preferred RBs. Since the Preferred RBs might different among D2D pairs, the Available RBs might also different among D2D pairs.

After finding the Available RBs, they are first allocated to coalitions and, then, to the D2D pairs in a coalition. Let $\mathbf{B}_i^{\mathrm{RB}}$ be the set of Available RBs of D2D pair i. This set will be updated whenever an Available RB is allocated. The steps to allocate

Available RBs to coalitions are illustrated in Table 1. For simplicity, we use RB in Table 1 to represent the Available RB. In addition, in any case, only consecutive Available RBs can be allocated to coalitions and D2D pairs.

Following, we will explain how to allocate Available RBs to coalitions obtained by employing the flow chart in Fig. 2 to the example network in Fig. 3. As described in Table 1, eNB allocates Available RBs to coalitions based on the order that coalition is formed. Hence, Fig. 4 shows how eNB allocates Available RBs to $\mathbf{C}_1$. We assume each CU is allocated with 3 RBs. From the third row to the seventh row, a “1” indicates that the corresponding RB is an Available RB of the D2D pair; otherwise, it is a “0”. Since D2D pair **a** is the only member in $\mathbf{C}_1$, according to the third row of Table 1, we have $\mathbf{I} = \mathbf{J} = \mathbf{K} = \mathbf{L} = \{0, 1, 2, 3, 4, 5\}$. Since $N_{1,total}^{RB,req} = 3$ and $|\mathbf{K}| = 6$, there are 4 RB allocation combinations, $\{0, 1, 2\}$, $\{1, 2, 3\}$, $\{2, 3, 4\}$, and $\{3, 4, 5\}$. To increase the RB utilization, the one with the smallest total popularity value is selected. The popularity value of an Available RB of a D2D pair is defined as the ratio of the number of D2D pairs that also regard this RB as an Available RB and the total number of D2D pairs in the network. For example, the popularity value of RB 3 of D2D pair **a** is $(1 + 1 + 0 + 0 + 1)/5 = 0.6$. As shown in Fig. 4, the total popularity value of $\{0, 1, 2\}$ is the smallest among others. Hence, they are allocated to $\mathbf{C}_1$. Since there is only D2D pair **a** in $\mathbf{C}_1$, allocating Available RBs to $\mathbf{C}_1$ is equivalent to allocating Available RBs to D2D pair **a**.

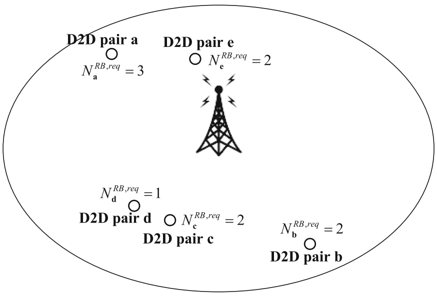

Fig. 3. An example network with 5 D2D pairs and the number of demanded RBs.

RB No.	0	1	2	3	4	5	6	7	8	9
CU No.	0	0	0	1	1	1	2	2	2	3
$\mathbf{B}_a^{RB}$	1	1	1	1	1	1	0	0	0	0
$\mathbf{B}_b^{RB}$	0	0	0	1	1	1	1	1	1	0
$\mathbf{B}_c^{RB}$	1	1	1	0	0	0	1	1	1	0
$\mathbf{B}_d^{RB}$	0	0	0	0	0	0	1	1	1	1
$\mathbf{B}_e^{RB}$	0	0	0	1	1	1	0	0	0	0
I=J=K=L	1	1	1	1	1	1	0	0	0	0
Popularity **a**	0.4	0.4	0.4	0.6	0.6	0.6	0	0	0	0
Allocation	**a**	**a**	**a**	0	0	0	0	0	0	0

Fig. 4. Available RB allocation for C_1.

Next, eNB allocates Available RBs to $\mathbf{C}_2$ in which $N_{2,total}^{RB,req} = 4$. However, as shown in Fig. 5 which is obtained from Fig. 4, $\mathbf{I} = \mathbf{K} = \{6, 7, 8\}$ and $\mathbf{J} = \mathbf{L} = \{0, 1, 2, 3, 4, 5, 6, 7, 8\}$. Based on Table 1, RBs in **K** will be first allocated to $\mathbf{C}_2$. Then, by removing RBs in **K** from **L**, $\mathbf{L} \backslash \mathbf{K} = \{0, 1, 2, 3, 4, 5\}$. To meet the RB continuity requirement, RB 5 is selected and allocated to $\mathbf{C}_2$. However, how to further allocate RBs 5, 6, 7, and 8 to D2D pairs **b** and **c** will be mentioned later.

Finally, eNB allocates Available RBs to $\mathbf{C}_3$ in which $N_{3,total}^{RB,req} = 3$. From Fig. 6 which is also obtained from Fig. 4, we know $|\mathbf{K}| = 0$. Hence, by employing the greedy algorithm to allocate Available RBs with the highest SINR to D2D pairs in $\mathbf{C}_3$, RBs 3 and 4 are allocated to D2D pair **e** and RB 9 is allocated to D2D pair **d**.

Now, we will explain how to further allocate Available RBs to D2D pairs in $\mathbf{C}_2$. The allocation of Available RBs to D2D pairs in a coalition is modelled as a Nash Bargaining game in which the players are the D2D pairs in the coalition, the goods are the Available RBs allocated to the coalition, and the payoff of an Available RB is its capacity. The NBS of a Nash Bargaining game can be obtained by the following formula:

$$\underset{R_{q,1},R_{q,2},\ldots,R_{q,|\mathbf{C}_q|}}{\arg \max} \prod_{m=1}^{|\mathbf{C}_q|} \left(R_{q,m} - R_{\min}^{q,m}\right), \tag{4}$$

where $|\mathbf{C}_q|$ is the number of D2D pairs in $\mathbf{C}_q$, $R_{\min}^{q,m}$ is the minimum acceptable capacity of the m-th D2D pair in $\mathbf{C}_q$ and is set to 0, $R_{q,m}$ is the capacity of the m-th D2D pair in $\mathbf{C}_q$ and is calculated based on (2). In our problem, among all possible RB allocation combinations, NBS is to find one whose resulting set of $R_{q,m}$ satisfies (4). Furthermore, in the Nash Bargaining game, the number of Available RBs assigned to the D2D pair is based on the number of RBs it demands. In case of the number of Available RBs allocated to $\mathbf{C}_q$ is less than the total number of demanded RBs of the D2D pairs in $\mathbf{C}_q$, the number of Available RBs allocated to each D2D pair in $\mathbf{C}_q$ is proportional to the number of RBs it demands.

From Fig. 5, among the four allocated RBs, RB 5 can only be used by D2D pair **b**. In this case, without violating the RB continuity requirement, the NBS, i.e., the solution to (4), is to allocate RBs 5 and 6 to D2D pair **b**, while RBs 7 and 8 to D2D pair **c** as listed in the last row of Fig. 5 under the assumption that the SINRs of RBs 6, 7, and 8 perceived at D2D pairs **b** and **c** are the same.

Table 1. Steps to allocate RB to coalitions.

for each coalition $\mathbf{C}_q$, q=1, 2, $\cdots$
  $\mathbf{I} = \bigcap_{i\in\mathbf{C}_q} \mathbf{B}_i^{\mathrm{RB}}$ and $\mathbf{J} = \bigcup_{i\in\mathbf{C}_q} \mathbf{B}_i^{\mathrm{RB}}$
  K is the set of RBs selected from the largest
  consecutive RBs in **I**.
  L is the set of RBs selected from the largest
  consecutive RBs in **J** that contains **K**.
  if $|\mathbf{K}|=0$
    Allocate RBs by greedy algorithm.
  else if $|\mathbf{K}| \geq N_{q,total}^{RB,req}$
    Allocate $N_{q,total}^{RB,req}$ RBs from **K**.
  else
    Allocate $|\mathbf{K}|$ RBs from **K** and at most
    ($N_{q,total}^{RB,req}$ $-|\mathbf{K}|$) RBs from $\mathbf{L}\backslash\mathbf{K}$.
  end if
  end if
end for

RB No.	0	1	2	3	4	5	6	7	8	9
CU No.	0	0	0	1	1	1	2	2	2	3
I=K	0	0	0	0	0	0	1	1	1	0
J=L	1	1	1	1	1	1	1	1	1	0
Allocation	0	0	0	0	0	1	1	1	1	0
NBS						**b**	**b**	**c**	**c**	

Fig. 5. Available RB allocation for $\mathbf{C}_2$.

RB No.	0	1	2	3	4	5	6	7	8	9
CU No.	0	0	0	1	1	1	2	2	2	3
I=K=L	0	0	0	0	0	0	0	0	0	0
J	0	0	0	1	1	1	1	1	1	1
Allocation	0	0	0	**e**	**e**	0	0	0	0	**d**

Fig. 6. Available RB allocation for C_3.

4 Simulation Results

In this simulation, the CUs and D2D pairs are randomly and evenly distributed within the coverage of the considered eNB under the condition that each D2D pair is at least 35 meters away from the eNB [9]. In each simulation run, the positions of D2D pairs and CUs, the number of demanded RBs of each D2D pair, and the channel condition are randomly generated. We assumed the RB allocation cycle, i.e., how long the RB allocation take place, follows the semi-persistent RB scheduling cycle which is usually between 20 ms to 600 ms. In the simulation, $\alpha_{max} = 9$, $\alpha_{min} = 1$, and $SINR_{th}^{RB,D2D} = 30$ dB. The rest of parameter values used in the simulation are listed in Table 2. In Table 2, X is a lognormal random variable with zero mean and standard deviation σ. The presented results are the average of the results collected in 1,000 simulations.

Table 2. Simulation parameters.

Parameter	Value
Cell radius	500 m
Carrier frequency	2 GHz
System bandwidth	10 MHz
Pathloss for D2D link [9]	Max(20log(d[m]) + 38.44, 22.7log(d[m]) + 33.02) + X, $d \leq 17.06$ Max(20log(d[m]) + 38.44, 40log(d[m]) + 11.73) + X, $d > 17.06$
Pathloss for cellular link [10]	22log(d[m]) + 34.02 + X, $d \leq 320$ 40log(d[m]) − 11.02 + X, $d > 320$
Standard deviation σ	D2D: 7 dB, CU: 4 dB
Transmission power	CU: 23 dBm, D2D: 20 dBm, 23 dBm (default)
Noise spectral density	−174 dBm/Hz
N_C	10
N^{coal}	10
ε	1
dis^{max}	50 m

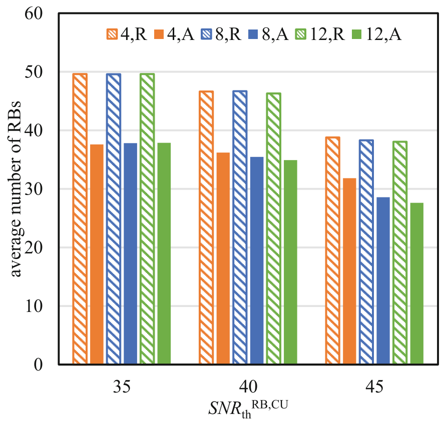

Fig. 7. The average numbers of Reusable (R) and Available (A) RBs for $SNR_{th}^{RB,CU} = 35, 40 = 35, 40$, and 45 dB and $N_{D2D} = 4, 8$, and 12, respectively.

First, we demonstrate the relationship between $SNR_{th}^{RB,CU}$ and the average numbers of Reusable and Available RBs. In Fig. 7, the average number of Reusable and Available RBs decrease as $SNR_{th}^{RB,CU}$ increases. This is mainly because the condition for a RB to be regarded as a Reusable gets stricter as $SNR_{\mathrm{th}}^{\mathrm{RB,CU}}$ increases. Besides, we also find the number of D2D pairs has very limited effect on the average number of Reusable RBs. However, due to the increase of the interference as the number of D2D pairs increases, the average number of Available RBs decreases.

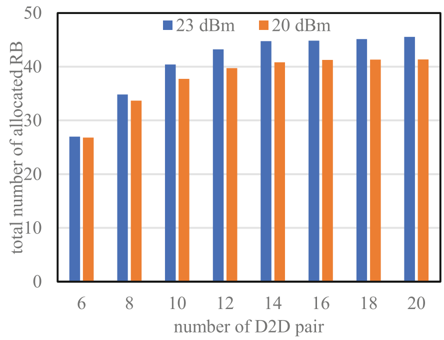

Fig. 8. The total number of allocated RB for different number of D2D pair.

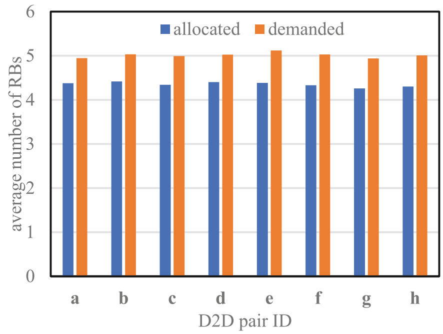

Fig. 9. The average number of demanded and allocated RBs for each D2D pair.

Figure 8 shows the total number of RBs allocated to D2D pairs with respect to different numbers of D2D pairs when $SNR_{th}^{RB,CU}$ = 40 dB. From the figure, when the number of D2D pairs increases, the total number of allocated RBs also increases. Furthermore, as the number of D2D pairs equals or great than 14, the total number of allocated RBs is about 45 which approaches the number of Reusable RBs indicated in Fig. 7. This means that almost all Reusable RBs are allocated to D2D pairs. In other words, almost 100% of the Reusable RBs are reused by the D2D pairs. We also noted that the total number of allocated RBs when the transmission power of D2D pair is 20 dBm is less than that when the transmission power of D2D pair is 23 dBm. This is mainly because as the transmission power is reduced, the SINR of D2D pair is also reduced, which results in the reduction of the number of Available RBs.

Finally, if there are 8 D2D pairs and $SNR_{th}^{RB,CU}$ = 40 dB, the number of demanded RBs and the average number of allocated RBs for each of the eight D2D pairs are shown in Fig. 9. Since $\alpha_{max} = 9$ and $\alpha_{min} = 1$, it can be seen from Fig. 9 that the average number of demanded RBs is approximately 5. In other words, the total number of demanded RBs is about 40. But, as shown in Fig. 7, about 35.5 RBs are allocated to the 8 D2D pairs. In this case, as shown in Fig. 9, each D2D pair is proportional fairly to be allocated about 4.4 RBs.

5 Conclusions

To solve the D2D radio resource allocation under the condition of sharing CU uplink RBs, this paper takes the numbers of demanded RBs of D2D pairs into account and uses the total number of demanded RBs in a coalition as the criterion to group D2D pairs into coalitions. By taking the intersection and union of the Available RBs, Available RBs are allocated to coalitions. Furthermore, when needed, the Nash Bargaining Solution is used to further allocate RBs to D2D pairs inside a coalition. Simulation results show that the proposed RB allocation scheme not only almost 100% reuses the Reusable RBs but also allocates Available RBs to D2D pairs inside a coalition in a proportional fairness way.

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