

# Loading-Balance Relay-Selective Strategy Based on Stochastic Dynamic Program

Wei Zhao\*, Lin Zhao, Weidong Wu, Sigen Chen, Shaohui Sun, and Yong Cao

**Abstract:** A Relay-Assisted (RA) network with relay selection is considered as a type of effective technology to improve the spectrum and energy efficiency of a cellular network. However, loading balance of the assisted relay node becomes an inevitable bottleneck in RA network development because users do not follow uniform distribution. Furthermore, the time-varying channel condition of wireless communication is also a major challenge for the RA network with relay selection. To solve these problems and improve the practicability of the RA network, a Loading Balance-Relay Selective (LBRS) strategy is proposed for the RA network in this paper. The proposed LBRS strategy formulates the relay selection of the RA network under imperfect channel state information assumption as a Multistage Decision (MD) problem. An optimal algorithm is also investigated to solve the proposed MD problem based on stochastic dynamic program. Numerical results show that the performance of the LBRS strategy is better than that of traditional greedy algorithm and the former is effective as an exhaustive search-based method.

**Key words:** relay-assisted network; relay selection; stochastic dynamic program

## 1 Introduction

A Relay-Assisted (RA) network is an effective method to improve the throughput of a system. Such a network is also considered as a more flexible and economical deployment plan than the macro-only system. Thus, many researchers have focused on studying this field. For example, in Ref. [1], widely adopted transfer protocols, namely, Amplify-and-Forward (AF) and Decode-and-Forward (DF), are proposed. Based on this study, various relay-selective strategies are proposed according to different optimal problems. References [2–4] studied the relay selective strategy to improve Spectrum Efficiency (SE) based on the harmonic mean of Source-Relay (SR)

and Relay-Destination (RD) channel gains. References [5, 6] investigated energy-efficient relay selection in a cognitive radio RA network and a battery-supplied RA network, respectively. All of the afore-mentioned studies have improved the practicability of the RA network.

However, because users and communication services are not uniform, some relay nodes tend to suffer from heavy loading while adjacent relay nodes maybe idle or carry only a light load. This type of loading unbalance not only limits the performance of the RA network but also wastes energy. Thus, the loading balance of the RA network has become a popular research topic. References [7–12] discussed the relationship among SE, Energy Efficiency (EE), and loading condition. References [13–16] designed an index to measure the loading condition based on the Signal-to-Noise Ratio (SNR) and quality of service. Furthermore, an optimal algorithm is proposed in Refs. [13, 16] to cooperate with the designed index. In Refs. [17–20], channel borrowing and loading transfer are proposed to balance the loading in the traditional cellular network. The channel borrowing adjusts the load of a base station by sharing channels, and the loading transfer

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adjusts the load by switching the servicing base station. However, neither channel borrowing nor loading transfer can be used in the RA network because it is developed for the homogeneous network. Additional costs are also required to support channel sharing or service switching. To overcome this drawback, Refs. [21–24] further studied power allocation and relay loading balance in an OFDMA-based RA network. References [25–27] adopted game theory to adjust the loading of the heterogeneous network.

Unfortunately, most of these studies developed their work under the assumption of perfect Channel State Information (CSI). This assumption limited the application of the results since it is hardly to obtain the perfect CSI in a practical scenario. Fortunately, the development of a Stochastic Dynamic Program (SDP) provides a new way to solve this problem. The relay selection with statistical CSI, which can be obtained through long-term, is a type of Multistage Decision (MD) problem. This problem can be solved effectively by SDP<sup>[28–30]</sup>.

The main contributions of this paper are the following. First, Loading Balance Relay Selective (LBRS) strategy is formulated as an MD problem. Second, the performance upper bound of the LBRS strategy is analyzed. Finally, SDP is adopted to solve the proposed multistage decision problem.

This paper is organized as follows. In Section 2, an AF RA network model is proposed. The frame structure and protocol of the LBRS strategy are also introduced. The signal model and optimal algorithm based on SDP are introduced in Section 3. In Section 4, the numerical results of the proposed optimal algorithm are reported. Finally, the conclusion is drawn in Section 5.

## 2 System Model and Problem Formulation

In this section, the AF RA model and the protocol of the LBRS strategy are proposed.

### 2.1 System model

In this paper, we consider a typical wireless RA network that includes multiple users and multiple relay-assisted candidates (Fig. 1). As a result of the time-varying channel condition, the user nodes require at least one relay node to assist the communication. Furthermore, the widely known AF protocol is adopted in this study.

We assume that each assisted relay works with multiple user nodes by frequency division. The user nodes negotiate with each Assisted-Relay Candidate (ARC) to select the suitable one. Without loss of generality, the flat fading

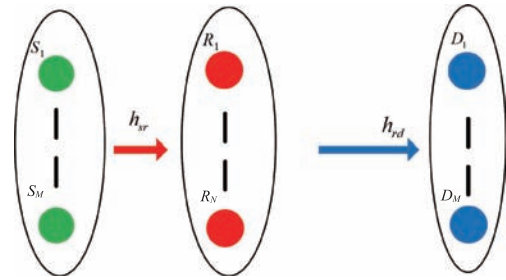


Fig. 1 An illustration of the RA network with multiple users and assisted relay candidates.

channel with Gaussian noise is adopted in this paper.

### 2.2 Frame structure

In this paper, Time Division Duplexing (TDD) protocol is employed. Thus, the communication process can be divided into serial time slots. Each slot is further divided into negotiation and transmission stages. During the negotiation stage, the user node negotiates with ARC in sequence and determines whether to adopt it. If a candidate is adopted, the user node turns to the transmission stage. Furthermore, because the AF protocol is used, the transmission stage can also be divided into two steps. First, the adopted ARC receives the signal of the source node. Second, the signal is relayed to the destination nodes. The TDD structure is presented in Fig. 2.

### 2.3 Protocol of LBRS strategy

As shown in Fig. 3, the user node has two choices during the negotiation stage. If the negotiating assisted-relay candidate is accepted, the source node proceeds to the transmission stage. If the negotiating candidate is

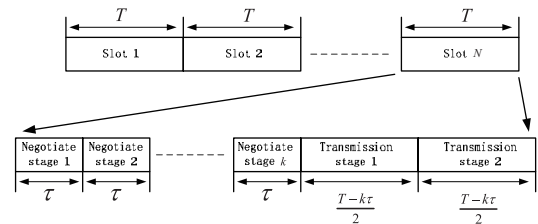


Fig. 2 An illustration of the frame structure of the LBRS strategy.

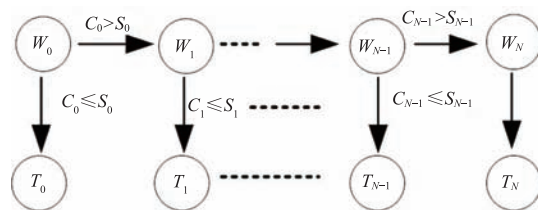


Fig. 3 An illustration of the protocol of the LBRS strategy.

already rejected, it turns to the next ARC and continues negotiating. During each slot, the user node negotiates with each candidate only once. Thus, the rejected candidates are not considered again until they reach the next communication slot.

Based on the preceding discussion, the protocol of the LBRs strategy is presented in Fig. 3. The figure shows a serial optimal threshold  $S_i$  ( $i = 1, 2, \dots, N-1$ ). When the source node negotiates with the  $i$ -th assisted relay candidate, it evaluates the channel rate  $C_i$  based on the relay loading and channel state. If  $C_i$  is larger than  $S_i$ , the  $i$ -th ARC is accepted. Otherwise, it is rejected. The last candidate has to be adopted if the first  $N-1$  assisted-relay candidates are rejected.

### 3 Optimal Algorithm of Threshold

In this section, the optimal algorithm of threshold is proposed.

#### 3.1 Signal model of LBRs strategy

As the two-hops AF protocol is employed by the LBRs strategy, the received signal of the relay node can be formulated as

$$y_i = h_{si} \sqrt{P_s} x + n_i \quad (1)$$

where  $y_i$  is the received signal of the  $i$ -th assisted relay candidate,  $h_{si}$  is the channel gain between the source and the  $i$ -th ARC,  $P_s$  is the transmit power of source,  $x$  is the transmit signal, and  $n_i$  is the noise variable of the  $i$ -th assisted-relay candidate. Similarly, the received signal of the destination is formulated as

$$y_d = \beta h_{id} y_i + n_d = \beta h_{id} h_{si} \sqrt{P_s} x + \beta h_{id} n_i + n_d \quad (2)$$

where  $y_d$  represents the received signal of the destination node,  $h_{id}$  represents the channel gain between the  $i$ -th assisted-relay candidate and the destination node, and  $n_d$  is the noise variable of the destination node.  $\beta$  is the magnification coefficient.

$$\beta = \sqrt{\frac{P_i}{|h_{si}|^2 P_s + \sigma_i^2}} \quad (3)$$

where  $P_i$  is the transmit power of the  $i$ -th ARC, and  $\sigma_i^2$  is the variance of  $n_i$ . If we further denote  $\sigma_d^2$  as the variance of  $n_d$ , then  $\beta h_{id} n_i + n_d$  follows the Gaussian distribution  $N(0, \beta^2 h_{id}^2 \sigma_i^2 + \sigma_d^2)$ . When the maximal radio combining protocol is adopted, the SNR of the receive signal of the destination node can be written as

$$\gamma = \frac{P_s P_i |h_{si}|^2 |h_{id}|^2}{P_s |h_{si}|^2 \sigma_d^2 + P_i |h_{id}|^2 \sigma_i^2 + \sigma_i^2 \sigma_d^2} \quad (4)$$

So the channel rate of the relay link is calculated as

$$C = \frac{1}{2m} \log_2(1 + \gamma), \quad m = 1, 2, \dots, m_{max} \quad (5)$$

$m_{max}$  is the total number of users in the RA network. Equation (5) shows that the channel rate of the relay link degrades sharply when the relay node is serving an extremely large number of users. If we further consider the negotiation cost, the channel rate with the  $i$ -th ARC  $C_i$  can be represented as

$$C_i = \frac{T - i\tau}{2m_i} \log_2(1 + \gamma_i), \quad i = 1, 2, \dots, N; \quad (6)$$

$$m_i = 1, 2, \dots, M$$

where  $T$  is the duration time of the slot, and  $\tau$  represents the negotiation cost. To achieve the best channel rate, the source node pursues the relay candidate that can establish a relay link with the maximal channel rate  $C_i$ . In this paper, this candidate is denoted as the Best ARC (BARC), which can be represented as

$$i^* = \arg \max \left\{ \sum_i C_i(m_i, \gamma_i) I_i \mid i = 1, 2, \dots, N \right\} \quad (7)$$

where  $I_i$  represents the indicator function, which can be represented as

$$I_i = \begin{cases} 1, & i^* = i; \\ 0, & \text{else} \end{cases} \quad (8)$$

To identify the BARC, the threshold of the LBRs strategy should be set as

$$S_{B,j} = \max \{ C_i(m_i, \gamma_i) \mid i = 1, 2, \dots, N \}, \quad (9)$$

$$j = 1, 2, \dots, N$$

Unfortunately, the source node cannot obtain the exact value of  $S_{B,j}$  without negotiation due to the time variation  $m_i$  and  $\gamma_i$ . Even if the source node negotiates with all of the assisted-relay candidates to obtain the exact  $S_{B,j}$ , the negotiation cost sharply degrades the channel rate performance.

#### 3.2 Threshold determination algorithm based on SDP

To address the shortage caused by time variation  $m_i$  and  $\gamma_i$ , SDP is adopted to cooperate with the LBRs strategy. Instead of using instant information, SDP works with the statistical information of  $m_i$  and  $\gamma_i$ . Thus, Eq. (7) can be rewritten as

$$i^* = \arg \max \left\{ E_{m_i, \gamma_i} \left[ \sum_i C_i(m_i, \gamma_i) I_i \right] \right\}, \quad (10)$$

$$i = 1, 2, \dots, N$$

where  $E_{m_i, \gamma_i}[\cdot]$  represents the expectation on  $m_i$  and  $\gamma_i$ . As stated in Section 2, the source node has two options at each negotiation stage. If the waiting option is denoted as  $G$  and the transmission option as  $T$ , then the option set  $\psi$  can be denoted as

$$\psi_i = \{G_i, T_i\}, \quad i = 1, 2, \dots, N \quad (11)$$

Thus, Eq. (9) can be rewritten as

$$S_i = E_{m_i, \gamma_i} [C_i(m_i, \gamma_i) | \psi_i, \psi_{i+1}], \quad (12)$$

$$i = 1, 2, \dots, N - 1$$

The preceding equation clearly shows that  $S_N = 0$ .  $E_{m_i, \gamma_i} [C_i(m_i, \gamma_i) | \psi_i, \psi_{i+1}]$  denotes the condition expectation on  $m_i$  and  $\gamma_i$ . Equation (12) can be solved by the backtrack algorithm.

$$S_i = \sum_{\psi_{i+1}} p_{\psi_i, \psi_{i+1}} E_{m_{i+1}, \gamma_{i+1}} [C_{i+1}(m_{i+1}, \gamma_{i+1}) | \psi_i, \psi_{i+1}] \quad (13)$$

$p_{\psi_i, \psi_{i+1}}$  denotes the one step transition probability. We define  $p_{\psi_i, \psi_{i+1}}$  as

$$p_{\psi_i, \psi_{i+1}} = (p_{G_i, G_{i+1}} \quad p_{G_i, T_{i+1}}) \quad (14)$$

If the source node rejects the first  $N - 1$  assisted-relay candidates, the One-Step Transition Probability (OSTP)  $p_{\psi_{N-1}, \psi_N}$  is

$$p_{\psi_{N-1}, \psi_N} = (0 \quad 1) \quad (15)$$

Thus, the last-stage threshold but one can be written as

$$S_{N-1} = E_{m_N, \gamma_N} [C_N(m_N, \gamma_N) | \psi_{N-1}, \psi_N] = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} C_N(m_N, \gamma_N) f(m_N) f(\gamma_N) dm_N d\gamma_N \quad (16)$$

The other optimal threshold of the LBRS strategy can be written as

$$S_{i-1} = \sum_{\psi_i} E_{m_i, \gamma_i} [C_i(m_i, \gamma_i) | \psi_{i-1}, \psi_i] = p_{G_{i-1}, G_i} S_i + p_{G_{i-1}, T_i} V_i \quad (17)$$

The OSTP is

$$p_{\psi_{i-1}, \psi_i} = (p_{G_{i-1}, G_i} \quad p_{G_{i-1}, T_i}) = \left( \int_{-\infty}^{\infty} \int_{-\infty}^{S_i} f(m_i) f(\gamma_i) dm_i d\gamma_i \times \int_{-\infty}^{\infty} \int_{S_i}^{\infty} f(m_i) f(\gamma_i) dm_i d\gamma_i \right) \quad (18)$$

And the expectation of the channel rate  $V_i$  is

$$V_i = \int_{-\infty}^{\infty} \int_{S_i}^{\infty} C_i(m_i, \gamma_i) f(m_i) f(\gamma_i) dm_i d\gamma_i \quad (19)$$

From Eqs. (12)–(19), all of the thresholds of the LBRS strategy can be calculated. The process of the LBRS strategy is concluded in Table 1.

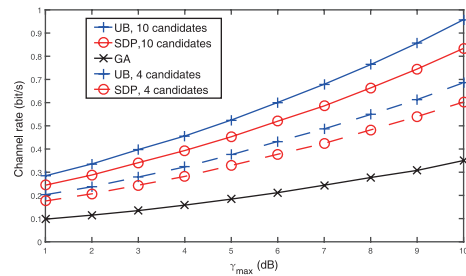
## 4 Simulation Results

In this paper, we report the numerical results of the LBRS strategy. We assume that all of the SNRs, which are provided by the assisted-relay candidates, follow the uniform distribution  $U(0, \gamma_{\max})$ . Furthermore, all of the relay loading  $m_i$  also follow the uniform distribution  $U(0, m_{\max})$ . We repeat the simulation 100 000 times.

In Fig. 4, the relationship between channel rate and  $\gamma_{\max}$  is shown. The max relay loading  $m_{\max}$  is 10. The blue line with plus represents the channel-rate upper bound of the LBRS strategy, which is obtained by the exhaustive search-based method when the source nodes have the perfect CSI without negotiation. The red line with a circle indicates the channel rate of the LBRS strategy with SDP. The black line with  $\times$  represents the performance of Greedy Algorithm (GA) when the source node always adopts the first ARC to avoid the negotiation cost. The solid line and dash line represent the channel rate of the

**Table 1 Loading-balance relay-selective strategy.**

- (1) Determine the threshold of the channel rate of the relay link.
- (2) Negotiate with the  $i$ -th ARC.
  - (a) Calculate the channel capacity of relay link  $C_{R,i}$ .
  - (b) If  $C_{R,i} > S$ , then the source node adopts the negotiating candidate and proceeds to the transmission stage.
  - (c) If  $C_i \leq S_i$ , then the negotiating candidate is rejected.
  - (d) The source node negotiates with the next candidate and returns to Step (a).
  - (e) If the first  $N - 1$  candidate is rejected, then the source node accepts the last ARC and turns to Step (4).
- (3) Transmission stage.

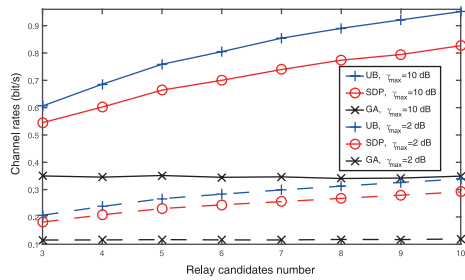


**Fig. 4 Channel rate performance of LBRS strategy under different SNR assumptions.**

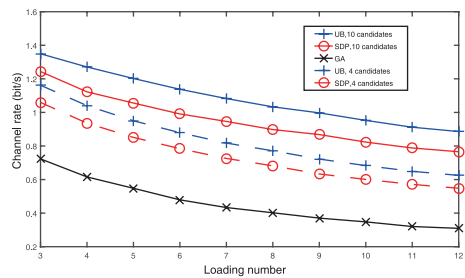
LBRS strategy when 10 and 4 assisted-relay candidates exist in the RA network, respectively. As the figure shows, the channel rate of the LBRS strategy increases with the increase of  $\gamma_{\max}$ . Furthermore, the channel rate of the LBRS strategy with SDP is superior to the channel rate of GA and achieves the channel-rate upper bound effectively. Meanwhile, the increase of the ARC number is also beneficial to the channel-rate LBRS strategy when SDP is employed.

Figure 5 shows the relationship between relay candidate number and channel rate. Similar to what is illustrated in Fig. 4, the blue line with plus represents the channel-rate upper bound of the LBRS strategy. The red line with a circle and black line with  $\times$  represent the channel rate performance of SDP and GA, respectively. The solid line and dash line denote results when  $\gamma_{\max}$  is 10 and 2 dB, respectively. The results presented in Fig. 5 are similar to those in Fig. 4. The channel rate increases with the increase of  $\gamma_{\max}$  and assisted-relay candidate number. Notably, the channel rate converges when the assisted-relay candidates number is sufficiently large. This condition means that redundant candidates are not always beneficial to the channel-rate performance of the LBRS strategy.

Figure 6 shows the relationship between relay-loading condition and channel rate. The meaning of the line is similar to that in the previous simulation. The results



**Fig. 5** Channel rate performance of LBRS strategy under different candidate number assumptions.

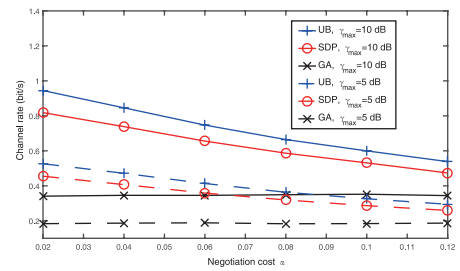


**Fig. 6** Channel rate performance of LBRS strategy under different loading condition.

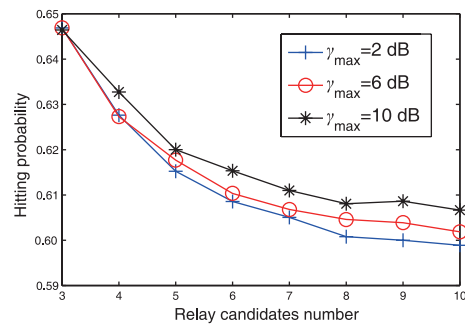
indicate that the channel rate of the LBRS strategy decreases with the increase of relay loading. This condition is consistent with our intuition. Although the channel rate of the LBRS strategy decreases with the increase of relay loading, it is superior to the performance of GA.

In Fig. 7, the relationship between negotiation cost and channel rate is shown. The meaning of the line is not changed. The channel rate of the LBRS strategy decreases with the increase of negotiation cost and close to the channel rate of GA. This result means that the LBRS strategy needs few assisted relay candidates when the negotiation cost increases because the source node prefers the first ARC.

Before the next simulation, we define the hitting probability as the probability that the channel rate performance of SDP can achieve the channel rate upper bound of the LBRS strategy. In Fig. 8, the blue line with plus represents the hitting probability when  $\gamma_{\max} = 2$  dB. Similarly, the red line with a circle and black line with a star represent the hitting probability when  $\gamma_{\max} = 6$  dB and  $\gamma_{\max} = 10$  dB, respectively. Figure 8 shows that the hitting probability decreases sharply with the increase of the assisted-relay candidate number. This result means that determining the BARC becomes difficult when a larger number of assisted-relay candidates exist in the RA network.



**Fig. 7** Channel rate performance of LBRS strategy under different negotiation cost assumptions.



**Fig. 8** Channel rate performance of LBRS strategy under different negotiation cost assumptions.

## 5 Conclusion

In this paper, a loading-balance relay-selective strategy is proposed for the relay-assisted network. Furthermore, SDP is investigated to cooperate with the proposed strategy. The analysis and numerical results prove that the LBRS strategy with SDP performs excellently.

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