Performance Analysis of Layer 1 Relays

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***Abstract*- Relays are expected to be included in 3GPP Release 10 also known as LTE-Advanced (LTE-A). Relays can be used to improve coverage and throughput and could be an important tool to improve the wireless experience. In this paper, the discussion on relay technologies in 3GPP LTE-A is overviewed firstly. Because both low cost and small delay make L1 relay more attractive than other types of relay, the SINR and information rate performance of L1 relays are analyzed mainly in this paper. With a simple one-dimensional relay model and an approximate self-interference model, the capability of L1 relays to improve cell-edge throughput is verified.**

***Keywords*- L1 relays, SINR, information rate**

I. INTRODUCTION

Relays are not a new concept: simple repeaters have been deployed since the 1980s. They have however not been implemented on a large scale for cellular systems. The only currently existing standard for relaying in cellular systems is IEEE802.16j. Relays are expected to be included in 3GPP Release 10 also known as LTE-Advanced (LTE-A) [1-3]. Relays can be used to improve coverage and throughput and could be an important tool to improve the wireless experience. Standardization work of relays is expected to begin early in 2009.

Contribution [4] defined L1, L2 and L3 relays according to the level where traffic is forwarded. L1 relays amplify and forward the received signals from the source at the physical layer. L2 relays decode and re-encode the received data blocks from source so that it can be viewed as forwarding the data at layer 2. The L3 relays forward the user-plane traffic data packet at the IP layer.

What makes L1 relays attractive is that they are low cost, introduce a small delay and have little impact on LTE Rel-8 specifications compared to other types of relay. With a simple one-dimensional relay model, this paper analyzes whether L1 relays can improve cell-edge throughput. The analysis results show that L1 relays perform well compared with the case of without relay. That means L1 relays are a potential candidate technology to achieve cell-edge throughput improvement for LTE-Advanced [5].

The remainder of the paper is organized as follows. Section II gives a brief overview of relay related discussion in LTE-A. Section III describes a simple one-dimensional relay model. In Section IV and V, the SINR and information rate performance of L1 relays are analyzed separately, and ~~numerical~~ results are also presented. This paper is summarized and concluded in section VI.

II. OVERVIES OF DISCUSSION ON RELAY IN 3GPP LTE-A

In 3GPP LTE-A, both definition and classification are the main discussion items. Relaying can be classified according to which layer is used to forward the data. Namely, three types of relaying are defined: L1, L2 and L3 relays. In the following sections, each type of relay is described.

2.1 L1 Relaying

An L1 relay is a slightly more advanced unit than simple repeater: it also amplifies and forwards both useful signal and noise/interference, but also can perform simple functions such as power control. Also, for some L1 relaying schemes, carrier-selective relaying can be performed. The user plane protocol stack is shown in Figure 1.

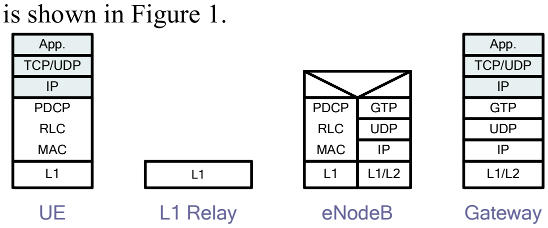

Figure 1. User plane protocol stack for L1 relays.

2.2 L2 Relaying

For the RAN1 working group, L2 relays have a major impact on standardization. The characteristics of L2 relaying are different than L1 relaying: L2 relays demodulate and decode the received signal, then re-encode and re-modulate the signal. Because of the additional processing, L2 relays cannot receive and transmit at the same time: there needs to be at least one subframe delay between the time a signal is received and the time it is sent.

L2 relays are more advanced units than L1 relays. They can perform some additional functionalities:

- The relay can change the Modulation/Coding scheme and or the transmit power when retransmitting the signal.
- With some L2 schemes, the relay can perform its own scheduling to do e.g., frequency scheduling or interference avoidance.
- It may be possible to do cooperative relaying.

However, these new functionalities require additional signaling messages. Additional messages must be designed between the base station and the relay, and between the relay and the UE.

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The user plane protocol of L2 relays is shown in Figure 2.

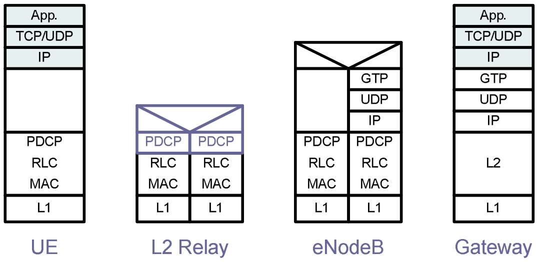

Figure 2. User plane protocol stack for L2 relays.

2.3 L3 Relaying

An even more advanced type of relaying is L3 relaying. A L3 relay is an eNodeB using the cellular link for backhauling. This type of relaying can be very important to improve the coverage zone of an eNodeB without incurring the cost of wiring another eNodeB. The user plane stack is shown in Figure 3.

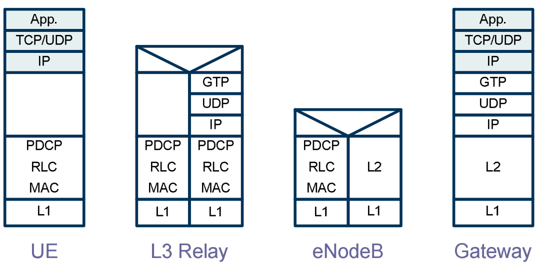

Figure 3. User plane protocol stack for L3 relays.

III. Analysis Model

In this section, we propose a simplified one-dimensional linear relay model as shown in Figure 4, where one source (S) communicates with one destination (D) with the help of one relay (R) in the environment with one interference (I). In this model, h_{XY} denotes the fast fading channel between X and Y, P_X denotes the transmit power of X, x_X denotes the transmitted signal from X, y_X denotes the received signal at X, n_X indicates AWGN for X, and σ_X^2 denotes the noise variance of X. L denotes the distance between S and R, ISD denotes the distance between S and I and d denotes the distance between R and D.

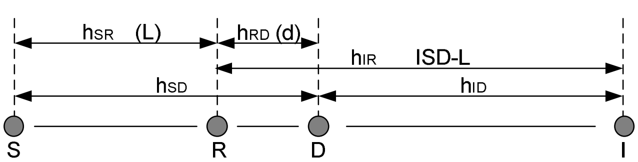

Figure 4. One-dimensional linear relay model.

The wireless fading channel, h_{XY}, is given by

$$h_{SD}(n) = PL_{SD} \sum_{m=1}^{N_{paths}} \alpha_{SD,m} \delta\left(n - \tau_{SD,m}\right), \tag{1}$$

$$h_{RD}(n) = PL_{RD} \sum_{m=1}^{N_{paths}} \alpha_{RD,m} \delta\left(n - \tau_{RD,m}\right), \tag{2}$$

$$h_{SR}(n) = PL_{SR} \sum_{m=1}^{N_{paths}} \alpha_{SR,m} \delta\left(n - \tau_{SR,m}\right), \tag{3}$$

$$h_{ID}(n) = PL_{ID}, \tag{4}$$

$$h_{IR}(n) = PL_{IR}, \tag{5}$$

where $h_{ID}(n)$ and $h_{IR}(n)$ are implicit modeling to reduce analysis complexity, and the path loss between any two nodes is given by[6]

$$L_{SD} = 128.1 + 37.6\log10(L+d) \rightarrow P_{SD,loss} = 10^{L_{SD}/10} \tag{6}$$

$$L_{SR} = 124.5 + 37.6\log10(L) \rightarrow P_{SR,loss} = 10^{L_{SR}/10} \tag{7}$$

$$L_{RD} = 140.7 + 36.7\log10(d) \rightarrow P_{RD,loss} = 10^{L_{RD}/10} \tag{8}$$

$$L_{ID} = 128.1 + 37.6\log10(ISD - L - d) \rightarrow P_{ID,loss} = 10^{L_{ID}/10} \tag{9}$$

$$L_{IR} = 124.5 + 37.6\log10(ISD - L) \rightarrow P_{IR,loss} = 10^{L_{IR}/10} \tag{10}$$

The received signals at destination and relay are given respectively by

$$\begin{aligned} y_D(n) &= h_{SD}(n) * x_S(n) + h_{ID}(n) * x_I(n) \\ &\quad + h_{RD}(n) * \left(g y_R(n)\right) + n_D \end{aligned} \tag{11}$$

$$y_R(n) = h_{SR}(n) * x_S(n) + h_{IR}(n) * x_I(n) + n_R \tag{12}$$

where the amplifying factor is given by

$$g = \sqrt{\frac{P_R}{\left\{\sum_{m=1}^{N_{path}} \left|\alpha_{SR,m}\right|^2\right\} P_S / P_{SR,loss} + P_I / P_{IR,loss} + \sigma_R^2}} \tag{13}$$

Since there is processing delay inside L1 relays, the CP length will affect the final information rate results. The analysis of self-interference will use the results of [7], where the bias function $c(\tau)$ is given by

$$c(\tau) = \begin{cases} 0 & \tau < -NT \\ (NT + \tau)/NT & -NT \le \tau < 0 \\ 1 & 0 \le \tau < \Delta \\ (NT - (\tau - \Delta))/NT & \Delta \le \tau < NT + \Delta \\ 0 & \tau \ge NT + \Delta \end{cases} \tag{14}$$

where N is the FFT size, T is the sample interval and Δ is the CP length. It should be noted that the time of reference, i.e. time-instant 0, should be the first path's arrival time of source. The bias function is illustrated in Figure 5.

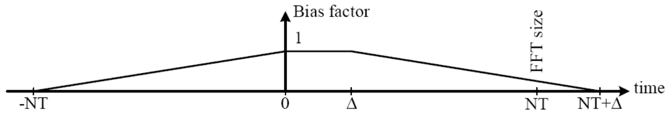

Figure 5: Bias function to reflect the influence of time delay

IV. SINR ANALYSIS

In this section we present the SINR expression of L1 relays using the model in Section III. The SINR of without relay case is also presented as a reference.

4.1 SINR of L1 relays

The "useful" signal power received by destination from source is given by

$$P_{SD,s} = \sum_{m=1}^{N_{paths}} c\left(\tau_{SD,m}\right)^2 E\left\{\left|\alpha_{SD,m}\right|^2\right\} \frac{P_S}{P_{SD,loss}}. \tag{15}$$

The interference signal power received by destination from source is given by

$$P_{SD,i} = \sum_{m=1}^{N_{paths}} \left(1 - c\left(\tau_{SD,m}\right)^2\right) E\left\{\left|\alpha_{SD,m}\right|^2\right\} \frac{P_S}{P_{SD,loss}}. \tag{16}$$

The "useful" signal power received by destination from L1 relays is given by

$$P_{RD,s} = \sum_{m=1}^{N_{paths}} \sum_{k=1}^{N_{paths}} \frac{g^2 c\left(\tau_{RD,m}\right)^2 E\left\{\left|\alpha_{RD,m}\right|^2\right\} E\left\{\left|\alpha_{SR,k}\right|^2\right\} P_S}{P_{SR,loss} P_{RD,loss}} \tag{17}$$

The interference signal power received by destination from L1 relays is given by

$$P_{RD,i} = \sum_{m=1}^{N_{paths}} \sum_{k=1}^{N_{paths}} \frac{g^2 \left(1 - c\left(\tau_{RD,m}\right)^2\right) E\left\{\left|\alpha_{RD,m}\right|^2\right\} E\left\{\left|\alpha_{SR,k}\right|^2\right\} P_S}{P_{SR,loss} P_{RD,loss}} \tag{18}$$

The interference power received by destination from interference is given by

$$P_{ID} = \sum_{m=1}^{N_{paths}} \frac{E\left\{\left|\alpha_{RD,m}\right|^2\right\} g^2 P_I}{P_{IR,loss} P_{RD,loss}} + \frac{P_I}{P_{ID,loss}}. \tag{19}$$

The noise power received by destination from L1 relays is given by

$$P_{RD,n} = \sum_{m=1}^{N_{paths}} E\left\{\left|\alpha_{RD,m}\right|^2\right\} g^2 \frac{\sigma_R^2}{P_{RD,loss}}. \tag{20}$$

The SINR of L1 relays with normal CP is given by

$$SINR_{L1} = \frac{P_{SD,s} + P_{RD,s}}{P_{SD,i} + P_{RD,i} + P_{RD,n} + P_{ID} + \sigma_D^2}. \tag{21}$$

4.2 SINR of without relay case

$$SINR_{w/o} = \frac{\sum_{m=1}^{N_{path}} E\left\{\left|\alpha_{SD,m}\right|^2\right\} P_S / P_{SD,loss}}{P_I / P_{ID,loss} + \sigma_D^2} \tag{22}$$

4.3 Numerical analysis results

The parameters for numerical analysis are given as Table 1 [6]. The TU channel model is considered for SINR analysis and the channel profile of the TU model is given in Table 2.

Table 1: Numerical analysis parameters

Parameters	Values
Sampling frequency	15.36MHz
length of normal CP	4.69μs
Distance between source and relay(L)	600/750m
ISD	1732m
Transmitted power by eNB	46dBm
Transmitted power by L1 relays	30dBm
Noise power	-104dBm

Table 2 TU channel profile

delay (μs)	gain (dB)
0.0	-3.0
0.2	0.0
0.5	-2.0
1.6	-6.0
2.3	-8.0
5.0	-10.0

Figure 6 and 7 show the SINR for L1 relays and without relay case when processing delay is 5μs. Figure 6 denotes SINR performance for a relay located at 600m away from source. Figure 7 denotes SINR performance for a relay located at 750m away from source. From the two figures, we can see that L1 relays outperform the without relay case in terms of SINR at cell edge.

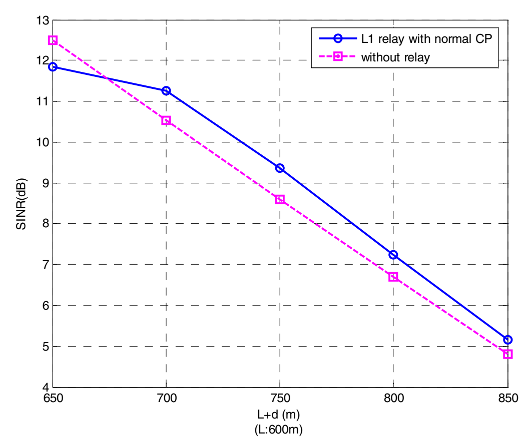

Figure 6. SINR performance of L1 relays vs. (L+d) when L=600m

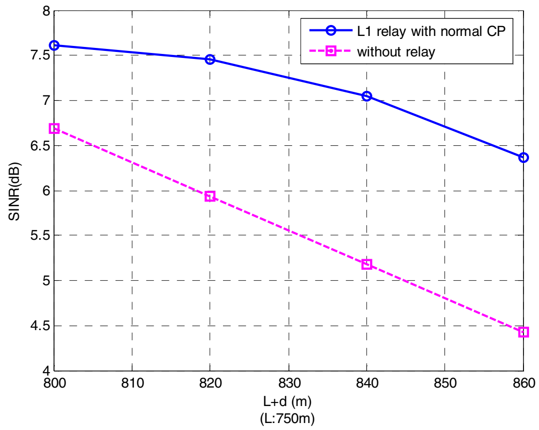

Figure 7. SINR performance of L1 relays vs. (L+d) when L=750m

The impact of different processing delay on SINR is depicted in Figure 8 and Figure 9 for different relay location, 600m or 750m. As we can see that when processing delay is not much longer than the length of CP, the processing delay has little impact on SINR, while long processing delay will degrade the SINR performance.

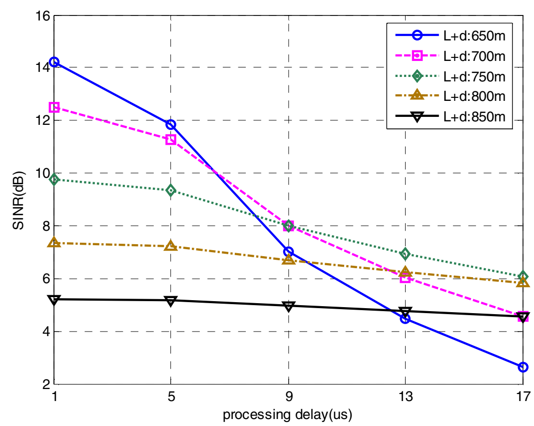

Figure 8. SINR performance of L1 relays vs. processing delay when L=600m

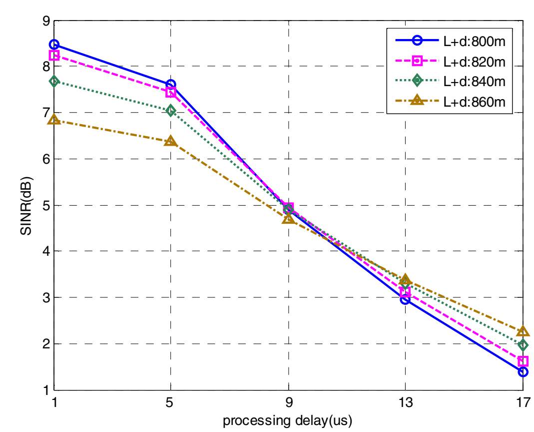

Figure 9. SINR performance of L1 relays vs. processing delay when L=750m

V. Information Rate Analysis

In this section we present the ergodic information rate expression of L1 relays using the model in Section III. The ergodic information rate expression of without relay case is also presented as a reference.

5.1 Information rate of L1 relays

The "useful" signal power received by destination from source with a given channel is given by

$$P_{SD,sc} = \sum_{m=1}^{N_{paths}} c\left(\tau_{SD,m}\right)^2 \left|\alpha_{SD,m}\right|^2 \frac{P_S}{P_{SD,loss}}. \tag{23}$$

The corresponding interference signal power is given by

$$P_{SD,ic} = \sum_{m=1}^{N_{paths}} \left(1 - c\left(\tau_{SD,m}\right)^2\right) \left|\alpha_{SD,m}\right|^2 \frac{P_S}{P_{SD,loss}}. \tag{24}$$

The "useful" signal power received by destination from L1 relays with a given channel is given by

$$P_{RD,sc} = \sum_{m=1}^{N_{paths}} c\left(\tau_{RD,m}\right)^2 \left|\alpha_{RD,m}\right|^2 g^2 \sum_{k=1}^{N_{paths}} \left|\alpha_{SR,k}\right|^2 \frac{P_S}{P_{SR,loss} P_{RD,loss}}. \tag{25}$$

The corresponding interference signal power is given by

$$P_{RD,ic} = \sum_{m=1}^{N_{paths}} \left(1 - c\left(\tau_{RD,m}\right)^2\right) \left|\alpha_{RD,m}\right|^2 g^2 \sum_{k=1}^{N_{paths}} \frac{\left|\alpha_{SR,k}\right|^2 P_S}{P_{SR,loss} P_{RD,loss}}. \tag{26}$$

The interference power received by destination from interference is given by

$$P_{ID,c} = \sum_{m=1}^{N_{paths}} \left|\alpha_{RD,m}\right|^2 g^2 \frac{P_I}{P_{IR,loss} P_{RD,loss}} + \frac{P_I}{P_{ID,loss}}. \tag{27}$$

The noise power received by destination from L1 relays is given by

$$P_{RD,nc} = \sum_{m=1}^{N_{paths}} \left|\alpha_{RD,m}\right|^2 g^2 \frac{\sigma_R^2}{P_{RD,loss}}. \tag{28}$$

The ergodic information rate of L1 relays is given by

$$R_{L1} = E \log_2\left(1 + \Gamma_{L1}\right). \tag{29}$$

where

$$\Gamma_{L1} = \frac{P_{SD,sc} + P_{RD,sc}}{P_{SD,ic} + P_{RD,ic} + P_{RD,nc} + P_{ID,c} + \sigma_D^2}. \tag{30}$$

5.2 Information rate of without relay case

The ergodic information rate for the case of without relay is given by

$$R_{w/o} = E \log_2\left(1 + \Gamma_{w/o}\right) \tag{31}$$

where

$$\Gamma_{w/o} = \frac{\sum_{m=1}^{N_{path}} \left|\alpha_{SD,m}\right|^2 P_S / P_{SD,loss}}{P_I / P_{ID,loss} + \sigma_D^2}. \tag{32}$$

5.3 Numerical analysis results

The parameters for numerical analysis are given as Table 1. To reduce analysis complexity without loss of generality, we assume N_{path}=1. The channels, $\alpha_{SD,m}$, $\alpha_{SR,m}$ and $\alpha_{RD,m}$ are modeled as complex Gaussian random variables with zero mean and unit variance.

Figure 10 and 11 show the information rate for L1 relays and without relay case when processing delay is 5μs. Figure 10 denotes information rate performance for a relay located at 600m away from source. Figure 7 denotes information rate performance for a relay located at 750m away from source. From the two figures, we can see that L1 relays outperform the without relay case in terms of information rate at cell edge.

The impact of different processing delay on information rate is depicted in Figure 12 and Figure 13 for different relay location, 600m or 750m. As we can see that when processing delay is not much longer than the length of CP, the processing delay has little impact on information rate, while long processing delay will degrade the information rate performance.

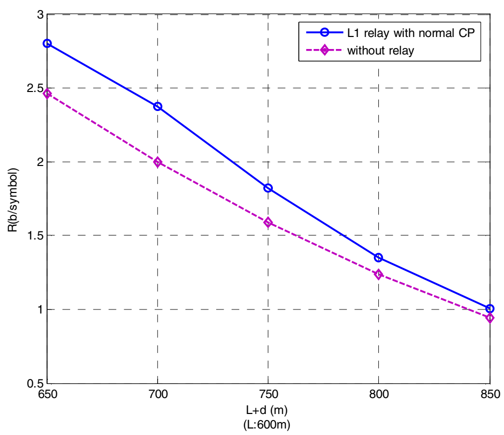

Figure 10. Information rate performance of L1 relays vs. (L+d) when L=600m

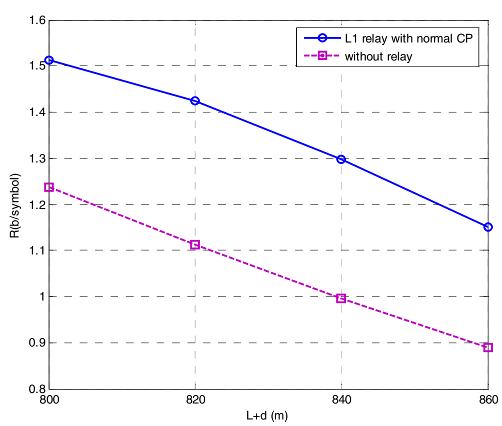

Figure 11. Information rate performance of L1 relays vs. (L+d) when L=750m

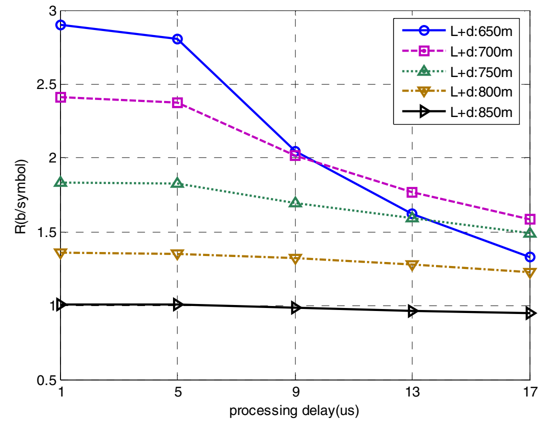

Figure 12. Information rate performance of L1 relays vs. processing delay when L=600m

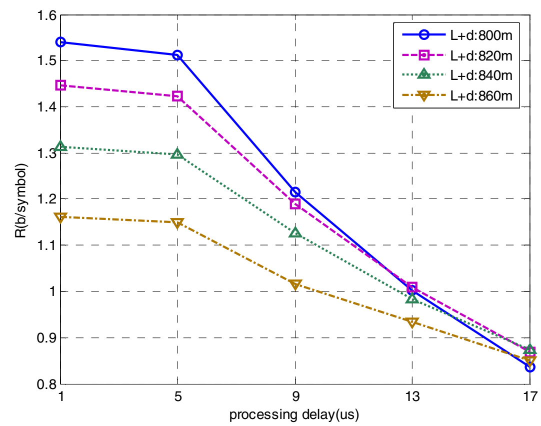

Figure 13. Information rate performance of L1 relays vs. processing delay when L=750m

VI. CONCLUSION

In this paper, we overviewed the current discussion on relay technologies in 3GPP LTE-A. According to the level where traffic is forwarded, the classification method, L1, L2 and L3 relays were introduced briefly. Because both low cost and small delay make L1 relay more attractive than other types of relay, the SINR and information rate performance of L1 relays were analyzed in this paper with a simple one-dimensional relay model and an approximate self-interference model. The numerical results shown that L1 relays could perform better than without relay case in terms of cell-edge SINR and cell-edge information rate. When processing delay is not much longer than the length of CP, the processing delay had little impact on SINR and information rate, while long processing delay degraded the SINR and information rate performance.

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