Study of Relay Selection in a Multi-cell Cognitive Network

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Abstract

This paper studies best relay selection in a multi-cell cognitive network with amplify-and-forward (AF) relays. We derive the analytical integral-form expression of the cumulative distribution function (CDF) for the received signal-to-noise-plus-interference-ratio (SINR) at the destination node, based on which the closed-form of the outage probability is obtained. Analysis shows that the proposed relay selection scheme achieves the best SINR at the destination node with interference to the primary user being limited by a pre-defined level. Simulation results are also presented to verify the analysis. The proposed relay selection approach is an attractive way to obtain diversity gain in a multi-cell cognitive network.

Index Terms

Relay selection, cognitive radio, multi-cell interference-limited networks

I. Introduction

Relay selection provides an attractive way to achieve diversity gain in cooperative networks [1]. While the relay may apply either a non-regenerative (e.g amplify-and-forward (AF)) or regenerative (e.g. decode-and-forward (DF)) protocol [2], this paper considers AF relaying due to its simplicity in implementation. Of particular interest is the outage probability which is perhaps the most important performance index for a relay selection system.

Early relay selection schemes were mainly for single-cell systems which normally include one source node, one destination node and a number of relays [3], where the best relay is selected to achieve the highest signal-to-noise-ratio (SNR) at the destination. The outage performance for single-cell relay selection has been well studied. It has been shown that the AF relay selection scheme can achieve full diversity order in a single-cell network [4], [5]. More recently relay selection is investigated in multi-cell wireless networks, where there are multiple cells and each cell has its own source, relay and destination nodes. Because of the interference from neighboring cells, the best relay in a multi-cell network is selected to achieve

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the highest signal-to-interference-plus-noise-ratio (SINR) at the destination. In [6], the relay selection for a two-cell network was investigated, where three kinds of best relay selection schemes were proposed. Further in [7], the outage performance of the system similar to that in [6] was analyzed based on the approximate SINR at the destination.

Relay selection in cognitive ratio (CR) networks has attracted much attention recently [**?**]. As a promising way to improve the spectrum efficiency, a CR network allows primary and secondary users to share frequency bands through various approaches including spectrum underlay, overlay and interweave [8]. Of particular interest in this paper is the underlay approach (due to its relatively straightforward practical implementation) where the interference from the secondary users to the primary users is strictly limited. Several relay selection schemes in CR networks have been investigated. For example, in [**?**] and [**?**], the authors analyzed the outage performance for the relay selection in a single-cell CR network which contains one primary user and one secondary transmitter-receiver pair with multiple relays.

In this paper, we consider a more general multi-cell CR network, where, besides the primary user, there are multiple secondary cells and each cell contains its own transmitting and receiving nodes. In the multi-cell CR network, because secondary transmitters interfere not only with the primary user but also with each other, the best relay is selected to achieve the highest SINR at the destination while at the same time it keeps the interference to the primary user within a pre-defined limit. Due to the inter-cell interference and interference limit to the primary user, the end-to-end SINR at the destination node no longer follows the MacDonald distribution unlike that in traditional AF relay-selection schemes [4]. This makes it very hard to obtain the distribution of the end-to-end SINR and the related outage probability. In fact, even for relay selection in a single-cell CR network, the outage probability is difficult to obtain [**?**] and [**?**]. The main contribution of this paper, therefore, is to derive the closed-form expression of the outage probability for the relay selection in a multi-cell CR network. The analysis not only provides a deep insight into understanding relay selection in an interference limited CR system, but also an interesting way in analyzing similar systems.

II. Relay selection in multi-cell cognitive networks

A cognitive radio network with $(K+1)$ cells is shown in Fig. 1, where there is one primary destination node PD, one target cell in which the relay selection is considered, and K neighboring cells. In the target cell, the secondary source SS transmits signals to the secondary destination node SD via N randomly scattered relays SR_i, $i=1,\cdots,N$. As in many existing approaches (e.g. [9]), we assume no direct link

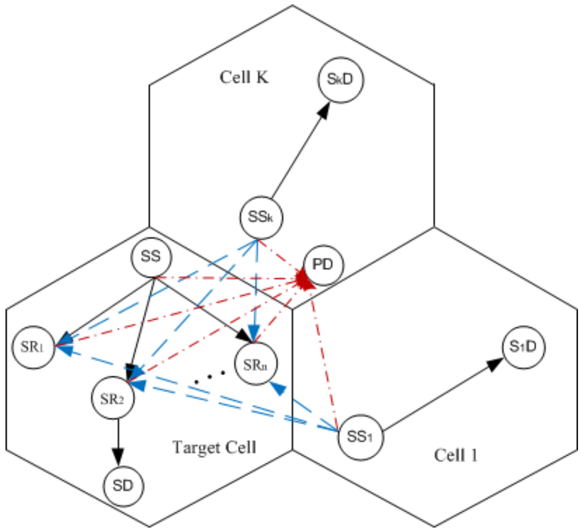

Fig. 1. A cognitive radio network with a target cell and K immediate neighbor cells, supporting primary and secondary transmissions through relay nodes.

between SS and SD[1]. In the kth neighboring cell ($k = 1, \cdots, K$), we assume without losing generality that there is one secondary source SS_k directly transmitting signals to the secondary destination S_kD[2].

The relays in the target cell apply the half duplex AF scheme: at the first time slot, SS broadcasts signals to all of the relays SR_i; at the second time slot, the best relay is selected to amplify and forward the received signals to SD. As is shown in Fig. 1, the $SS \rightarrow SR_i$ transmission suffers from K different inter-cell interferences from the neighboring secondary sources SS_k, $k = 1, \cdots, K$. Similar to many existing approaches such as those in [6], [10] and [11], we assume that the inter-cell interference at the target destination SD is much weaker than that at the relays so that it is ignored.

We assume that the nodes SS, SS_k and PD have significantly lower mobility than SR_i and SD. Thus the channels for $SS \rightarrow PD$ and $SS_k \rightarrow PD$, denoted as H_{sp}, H_{s_kp} respectively, vary little with time. And the corresponding channel gains, given by $G_{sp} = |H_{sp}|^2$ and $G_{s_kp} = |H_{s_kp}|^2$ respectively, can be regarded as constant (or be represented with their mean values). Note that similar assumption is also applied in many existing approaches including those in [12], [13] and [14].

On the other hand, we assume the channels $SS \rightarrow SR_i$, $SS_k \rightarrow SR_i$, $SR_i \rightarrow SD$, and $SR_i \rightarrow PD$, which are denoted as h_{sr_i}, $h_{s_kr_i}$, h_{r_id} and h_{r_ip} respectively, are independently Rayleigh flat fading, and keep unchanged within one packet but may vary from packet to packet. Therefore, the corresponding channel gains, obtained as $g_j = |h_j|^2$ $(j \in \{sr_i, s_kr_i, r_id, r_ip\})$ respectively, are independently exponentially distributed with mean of λ_j $(j \in \{sr_i, s_kr_i, r_id, r_ip\})$ respectively.

[1]Including the direct link has little effect on the relay selection which is the main issue in this paper.
[2]Including multiple relays in the neighboring cells does not change the nature of the relay selection in the target cell.

In the underlay cognitive system, the secondary transmission nodes including SS, SR_i and SS_k are only allowed to share the spectrum with the primary user PD if their interfering power to PD is below a certain level I_{th}. At the first time slot, SS broadcasts signals to all relays. We assume the worst case that, at the first time slot, the interference terms from all $(K+1)$ secondary sources to the primary user combine coherently. Then the transmission powers for SS and SS_k are constrained as

$$P_{ss}G_{sp} \leq \frac{I_{th}}{K+1}, \quad P_{ss_k}G_{s_kp} \leq \frac{I_{th}}{K+1}, \quad k = 1, \cdots, K, \tag{1}$$

respectively. The received signal vector at the ith relay SR_i is given by

$$\mathbf{y}_{sr_i} = h_{sr_i}\sqrt{\frac{I_{th}}{(K+1)G_{sp}}}\mathbf{s} + \sum_{k=1}^{K} h_{s_kr_i}\sqrt{\frac{I_{th}}{(K+1)G_{s_kp}}}\mathbf{s}_k + \mathbf{n}_{r_i}, \tag{2}$$

where $\mathbf{s}$ and $\mathbf{s}_k$ are transmission vectors from SS and SS_k respectively, and $\mathbf{n}_{r_i}$ is the noise vector at SR_i with zero mean and covariance matrix of $\sigma_r^2\mathbf{I}$.

At the second time slot, if the relay SR_i is used to amplify and forward the received signal to SD, its transmission power is constrained as

$$P_{sr_i}g_{r_ip} \leq I_{th}. \tag{3}$$

And the received signal vector at the destination SD is obtained as

$$\mathbf{y}_{r_id} = h_{r_id}\sqrt{\frac{I_{th}}{g_{r_ip}}}\beta\mathbf{y}_{sr_i} + \mathbf{n}_d, \tag{4}$$

where $\mathbf{n}_d$ is the noise vector at the destination with zero mean and covariance matrix of $\sigma_d^2\mathbf{I}$, and β is the amplifying factor at SR_i which is given by (e.g. see [15])

$$\beta = \frac{1}{\sqrt{\frac{g_{sr_i}I_{th}}{(K+1)G_{sp}} + \sum_{k=1}^{K}\frac{g_{s_kr_i}I_{th}}{(K+1)G_{s_kp}} + \sigma_r^2}}. \tag{5}$$

From (4) the instantaneous end-to-end SINR from SS to SD via SR_i can be obtained as

$$\gamma_{D_i} = \frac{\gamma_i^{(1)}\gamma_i^{(2)}}{\gamma_i^{(3)}(\gamma_i^{(2)}+1) + \gamma_i^{(1)} + \gamma_i^{(2)} + 1}, \tag{6}$$

where

$$\gamma_i^{(1)} = \frac{g_{sr_i}I_{th}}{(K+1)G_{sp}\sigma_r^2}, \quad \gamma_i^{(2)} = \frac{g_{r_id}I_{th}}{g_{r_ip}\sigma_d^2} \text{ and } \gamma_i^{(3)} = \sum_{k=1}^{K}\frac{g_{s_kr_i}I_{th}}{(K+1)G_{s_kp}\sigma_r^2}. \tag{7}$$

It is clear that $\gamma_i^{(1)}$ is exponentially distributed based on g_{sr_i}, $\gamma_i^{(2)}$ is the weighted ratio of two exponentially distributed variables g_{r_id} and g_{r_ip}, and $\gamma_i^{(3)}$ is the weighted sum of the exponentially distributed $g_{s_kr_i}$ for all $k = 1, \cdots, K$.

In this paper, we assume that perfect channel state information (CSI) is available at the relays and the target secondary destination[3]. With the CSI available, the secondary destination SD calculates the SINR γ_{D_i} for each of the relays as in (6), and chooses the relay with the largest SINR γ_{D_i} to forward the data. Because of the transmission power constraints at the source and relay nodes as in (1) and (3) respectively, the selected relay node with the highest SINR can ensure that the interference to the primary user is limited within the threshold I_{th}. To be specific, it is interesting to observe from (6) that, with an increase of $\gamma_i^{(1)}$ and $\gamma_i^{(2)}$, and reduction of $\gamma_i^{(3)}$, γ_{D_i} will be increased. This implies that the optimum relay balances the need for good links for $SS \rightarrow SR_i$ and $SR_i \rightarrow SD$, small interference from neighboring SS_k to SR_i and small interference from SR_i to the primary node PD.

III. Outage probability analysis

In this section, we first derive the exact expressions of the probability-density-function (PDF) and CDF of the end-to-end SINR in (6), and then obtain the outage probability for the overall system.

From [18], the PDF-s of $\gamma_i^{(1)}$, $\gamma_i^{(2)}$ and $\gamma_i^{(3)}$ are obtained as

$$f_{\gamma_i^{(1)}}(x) = \frac{1}{L_1} e^{-\frac{x}{L_1}}, \ f_{\gamma_i^{(2)}}(y) = \frac{L_2}{(L_2+y)^2} \quad \text{and} \quad f_{\gamma_i^{(3)}}(z) = \frac{z^{K-1} e^{-\frac{z}{L_3}}}{\Gamma(K) L_3^K} \tag{8}$$

respectively, where $\Gamma(K) = (K-1)!$ which is the complete Gamma function, K is the shape parameter representing the number of interfering cells, and

$$L_1 = \phi_1 \frac{I_{th}}{(K+1)\sigma_r^2}, \quad L_2 = \phi_2 \frac{I_{th}}{\sigma_d^2}, \quad \text{and} \quad L_3 = \phi_3 \frac{I_{th}}{(K+1)\sigma_r^2}, \tag{9}$$

where

$$\phi_1 = \frac{\lambda_{sr_i}}{G_{sp}}, \quad \phi_2 = \frac{\lambda_{r_id}}{\lambda_{r_ip}} \quad \text{and} \quad \phi_3 = \frac{\lambda_{s_kr_i}}{G_{s_kp}}, \tag{10}$$

which are the mean channel gain ratios. It is clear from (7) that $\gamma_i^{(1)}$, $\gamma_i^{(2)}$ and $\gamma_i^{(3)}$ are mutually independent.

[3]The CSI is usually estimated through pilots and feedback (e.g. [16]), and the CSI estimation without feedback may also be applied (e.g [17]). The detail of the CSI estimation is beyond the scope of this short letter.

Thus the joint PDF of $\gamma_i^{(1)}$, $\gamma_i^{(2)}$, $\gamma_i^{(3)}$ is given by

$$f_{\gamma_i^{(1)}\gamma_i^{(2)}\gamma_i^{(3)}}(x,y,z) = f_{\gamma_i^{(1)}}(x) f_{\gamma_i^{(2)}}(y) f_{\gamma_i^{(3)}}(z) = \frac{L_2}{L_1 \Gamma(K) L_3^K} \frac{z^{K-1} e^{-\frac{x}{L_1}} e^{-\frac{z}{L_3}}}{(L_2+y)^2}. \tag{11}$$

From (6) and (11), the CDF of γ_{D_i} can be obtained as

$$F_{\gamma_{D_i}}(\gamma) = P\left(\frac{\gamma_i^{(1)}\gamma_i^{(2)}}{\gamma_i^{(3)}(\gamma_i^{(2)}+1)+\gamma_i^{(1)}+\gamma_i^{(2)}+1} \le \gamma\right) = P\left(\gamma_i^{(1)} \le \frac{\gamma\gamma_i^{(3)}(\gamma_i^{(2)}+1)+\gamma_i^{(2)}\gamma+\gamma}{\gamma_i^{(2)}-\gamma}\right)$$
$$= \int_0^\infty \int_0^\gamma \int_0^\infty f_{\gamma_i^{(1)}\gamma_i^{(2)}\gamma_i^{(3)}}(x,y,z)dxdydz + \int_0^\infty \int_\gamma^\infty \int_0^{\frac{\gamma z(y+1)+y\gamma+\gamma}{y-\gamma}} f_{\gamma_i^{(1)}\gamma_i^{(2)}\gamma_i^{(3)}}(x,y,z)dxdydz, \tag{12}$$

where $P(.)$ denotes the probability value.

Substituting (11) into (12) gives

$$\begin{aligned} F_{\gamma_{D_i}}(\gamma) =& \frac{\gamma}{\gamma+L_2} + \frac{L_2}{\gamma+L_2}\left[1-\frac{L_1^N e^{-\frac{\gamma}{L_1}}}{(L_3\gamma+L_1)^N}\right] + \frac{L_2\gamma(\gamma+1)}{L_1\Gamma(K)L_3^K}\frac{1}{(L_2+\gamma)^2}\cdot \\ & \int_0^\infty z^{K-1}(1+z)e^{\frac{L_3\gamma(z+1)(1-L_2)-zL_1(L_2+\gamma)}{(L_2+\gamma)L_1L_3}} \wp\left(1, \frac{\gamma(\gamma+1)(1+z)}{(L_2+\gamma)L_1}\right)dz, \end{aligned} \tag{13}$$

where $\wp(a,b) = \int_1^\infty e^{-xb}x^{-a}dx$. Since $\lim_{x\to\infty} e^{-xb}x^{-a} = 0$, $\wp(a,b)$ can be approximated by replacing its infinite integral upper limit with a suitable large value.

In the underlay cognitive network, in order to facilitate the communications between SS and SD via SR_i and keep the interference to the primary destination PD at a low level, we usually have $\lambda_{sr_i} \gg G_{sp}$ and $\lambda_{r_id} \gg \lambda_{r_ip}$, leading to large L_1 and L_2 defined in (9). Then according to [19], (13) can be approximated as

$$\begin{aligned} F_{\gamma_{D_i}}(\gamma) \simeq & \frac{\gamma}{\gamma+L_2} + \frac{L_2}{\gamma+L_2}\left[1-\frac{L_1^N e^{-\frac{\gamma}{L_1}}}{(L_3\gamma+L_1)^N}\right] + e^{\frac{\gamma(1-L_2)}{(L_2+\gamma)L_1}} \cdot \frac{L_2\gamma(\gamma+1)}{L_1(L_2+\gamma)^2 L_3^K N(N+1)}\cdot \\ & \left\{\left[\frac{(L_2+\gamma)L_1}{\gamma(\gamma+1)}\right]^N (N+1)\ {}_2F_1(N,N;N+1;\nu_l) + \left[\frac{(L_2+\gamma)L_1}{\gamma(\gamma+1)}\right]^{N+1} N^2\ {}_2F_1(N+1,N+1;N+2;\nu_l)\right\}, \end{aligned} \tag{14}$$

where $\nu_l = \frac{L_3\gamma(1-L_2)-L_1(1+\gamma)}{(1+\gamma)\gamma L_3}$ and ${}_2F_1(a,b;c;z) = \frac{\Gamma(c)}{\Gamma(b)\Gamma(c-b)}\int_0^1 \frac{t^{b-1}(1-t)(c-b-1)}{(1-tz)^a}dt$ which is the hypergeometric function.

Finally, because the best relay is selected from N relays, from the theory of order statistics [20], the overall CDF of the SINR for $SS \rightarrow SD$ via the best relay is given by

$$F_{\gamma_D}(\gamma) = [F_{\gamma_{D_i}}(\gamma)]^N. \tag{15}$$

While the outage event occurs when the end-to-end SINR at the destination falls below a certain target level, from (15), the outage probability for the proposed relay selection system is given by

$$P_{out} = \int_0^{\alpha} f_{\gamma_D}(\gamma) d\gamma = F_{\gamma_D}(\alpha), \tag{16}$$

where α is the pre-defined target SINR.

IV. Simulations

In this section, simulation results are given to verify the above analysis. In the simulations below, the noise variances σ_r^2 and σ_d^2 and the signal transmission powers are all normalized to one.

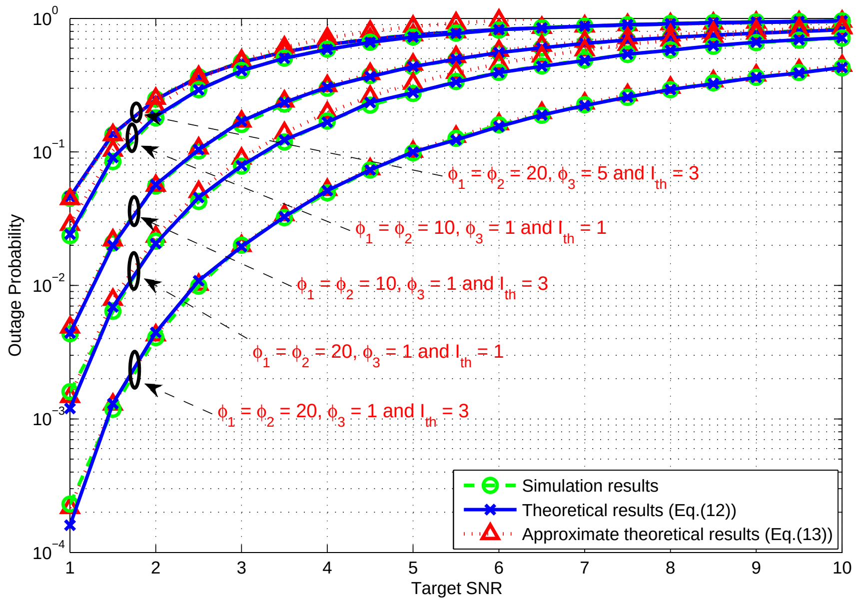

Fig. 2. Theoretical *vs* numerical outage probabilities, where the number of relays $N = 5$ and the number of neighboring cells $K = 3$.

Fig. 2 compares the theoretical analysis with the simulation results, where we let $\lambda_{SR_i} = \lambda_{R_iD} = 10$ dB, the number of available relays as $N = 5$ and the number of neighboring cells as $K = 3$. Both analytical results based on the exact expression (13) and those based on the approximation (14) are shown, and the simulation results are obtained by averaging over $50,000$ independent runs. The results are compared under different settings of the mean channel gain ratios ϕ_1, ϕ_2, ϕ_3 (defined (10)) and interference power threshold I_{th}. To be specific, we let $\phi_1 = \phi_2 = 20$ or 30, corresponding to large L_1 and L_2 defined in

(9). As was mentioned above, for large L_1 and L_2, the exact CDF of the SINR (13) can be approximated as (14). This is clearly verified in Fig. 2, where in all cases curves based on the exact expression (13), approximate expression (14) and numerical simulations are very well matched. It is also shown in Fig. 2 that the outage performance improves with larger I_{th}, but this is clearly at the price of higher interference to the primary source. At the same time, for the given ϕ_3 and I_{th}, increasing ϕ_1 and ϕ_2 also improves the outage performance. This is not surprising because with higher ϕ_1 and ϕ_2 the interference from SS and SR_i to PD becomes less, so that more power can be allocated for the SS and SR_i transmission. Fig. 2 also shows that a large ϕ_3 deteriorates the outage performance, because high ϕ_3 implies high interference from neighboring secondary sources SS_k to the relays SR_i.

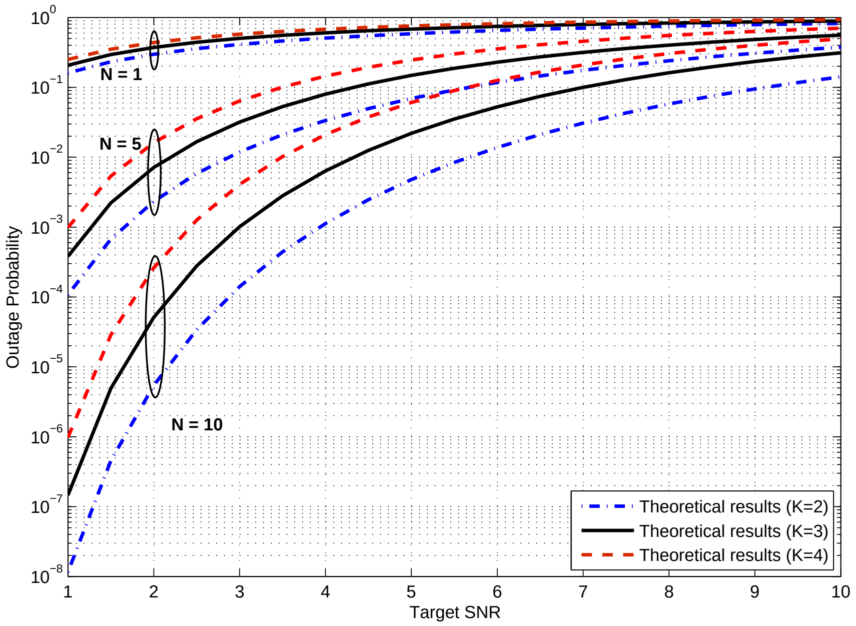

Fig. 3. Approximated results in (14) *vs* numerical outage probabilities for different numbers of relays N and neighboring cells K.

Fig. 3 compares the approximated theoretical results obtained with (14) and the simulation results for different numbers of relays N and neighboring cells K, where we let $\lambda_{SR_i} = \lambda_{R_iD} = 30$ dB, $\phi_1 = \phi_2 = 20$, $\phi_3 = 1$ and $I_{th} = 3$. It is clearly shown that, as N increase, the outage probability reduces, because higher diversity order can be achieved with larger N. At the same time, we can also observe that, the outage performance becomes worse with larger K since the relays experience higher multi-cell interference.

V. Conclusion

This papers described a best relay selection scheme in a multi-cell cognitive network. The closed-form of the outage performance of the proposed scheme was derived. The result showed that the best relay achieves highest SINR at the destination while it keeps the interference to the primary user within a predefined limit. We note that practical systems may be more complicated than the system considered in this paper. For instance, large scale fading may play an important role so that channels may not necessarily be i.i.d. fading, or relay selection is also carried out by other secondary users. While these present new interesting topics for future research, the analysis in this paper provides an effective way for further analysis.

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