Efficient Feasibility Examination for Successive Interference Cancellation in DS-CDMA Systems

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Abstract—On the uplink of a DS-CDMA system, successive interference cancellation (SIC) technique can be employed to reduce multiple access interference and improve system capacity. In such a system with \( K \) active users, there are \( K! \) possible decoding orders of SIC and not every decoding order is feasible due to some constraints. It is highly time-consuming to examine the system feasibility directly by using the exhaustive search method (ESM) for a system with even a moderate number of users. In this paper, we propose an efficient approach for examining the feasibility of DS-CDMA systems with imperfect SIC. The proposed approach has significantly less computational complexity than that of ESM, thus benefits the quick decision of admission control and/or scheduling in DS-CDMA systems. Furthermore, under the decoding order obtained by the proposed approach, we prove that the system is able to achieve the lowest outage probability among all possible decoding orders. Simulation experiments and numerical results validate our analysis and demonstrate the effectiveness of our approach.

Key Words—DS-CDMA, successive interference cancellation (SIC), decoding order, computational complexity

I. INTRODUCTION

DS-CDMA systems are interference-limited. In order to compete with wireless LANs and WiMax techniques in the long term, the capacity and data rates of DS-CDMA systems need to be substantially improved. Recently, successive interference cancellation (SIC), which is one of promising multi-user detection (MUD) techniques, draws more and more attentions for its low complexity and high performance[1]–[3]. Implementing SIC technique on the uplink of a DS-CDMA system can reduce multiple access interference and improve system capacity. The receiver with SIC technique detects (or decodes) the signals of individual users in sequence. Once a user is decoded, the received signal for this user can be estimated and reconstructed by appropriate channel estimation, and the reconstructed signal will be cancelled from the composite signal prior to decoding of subsequent users. The decoding order of SIC is of significance to the received signal qualities of individual users, as well as the overall system performance. Different decoding orders will inevitably result in different system performance. It is obvious that a system with \( K \) active users has \( K! \) possible decoding orders. Examining the system feasibility of \( K! \) possible decoding orders may bring in prohibitively high computational complexity and could become a barrier for implementing admission control and/or scheduling mechanisms which need the system feasibility information.

There has been some research work on the optimal decoding order of DS-CDMA systems with SIC in various aspects, such as minimizing the total transmission power [4], [5], maximizing the system capacity in terms of number of users [6] and maximizing the system throughput [7]. But none of them address the issue of examining the feasibility of DS-CDMA systems with imperfect SIC with realistic system constraints, especially, when the constraint of received power is considered. In [8]–[10], although the feasibility of DS-CDMA systems with imperfect SIC is involved, yet all the feasibility conditions are given only for one fixed decoding order. The issue of examining the feasibility of DS-CDMA systems with imperfect SIC with realistic system constraints is also not addressed.

In a real DS-CDMA system with SIC, the maximum transmission power of a mobile station is always limited, thus not every decoding order of SIC is feasible. Only if the bit-energy-interference ratio \( (E_b/I) \) requirement and power constraint are met under some decoding order, the system is feasible. Otherwise, if the constraints are always violated under all decoding orders, the system is infeasible. Intuitively, we need to check the feasibility of every decoding order one by one (called as the exhaustive search method, ESM) to identify the system feasibility. However, it is highly time-consuming to examine the system feasibility directly by using ESM for a system with even a moderate number of users. In the worst case, ESM needs to check all \( K! \) decoding orders until identifying that the system is feasible or infeasible. As essential components of Quality of Service (QoS) provisioning framework, the decision of admission control and/or scheduling, cannot be performed promptly, as they need the information of system feasibility. In this situation, the efficient examination of system feasibility is highly desired.

In this paper, we propose an efficient approach for examining the feasibility of DS-CDMA systems with imperfect SIC, where the received power is constrained. We can examine the system feasibility by checking only a specific decoding order which is obtained by the proposed approach. The computational complexity of the proposed approach is significantly reduced. Under the obtained decoding order, we theoretically prove that the system is able to achieve the lowest outage probability among all possible decoding orders. Noticeably, the proposed approach in this paper can be applied in QoS mechanisms designs, such as the designs of admission control and scheduling schemes which need the system feasibility information, in DS-CDMA systems.

The rest of this paper is organized as follows. In Section II,
we describe the system model. Section III presents our efficient approach for examining the feasibility of DS-CDMA systems with imperfect SIC. In Section IV, we present numerical results to validate our analysis and demonstrate the effectiveness of the proposed approach. Finally, Section V concludes this paper.

## II. SYSTEM MODEL

We consider a single cell DS-CDMA system consisting of a base station (BS) and $K$ users. The composite signal $y(t)$ received by the BS is composed of $X_i(t) = 1,2,\ldots,K$ ($X_i(t)$ is the received signal from the $i$-th user controlled by this BS), the interfering signal $I(t)$ due to the users controlled by other BSs, and the background noise $N(t)$. For the denotation simplicity, the total power of the interfering signal $I(t)$ and the background noise $N(t)$ is assumed to be fixed as $I_W$, where $W$ is the system bandwidth and $I_i$ is the corresponding power spectral density. The BS under consideration decodes users’ signals in sequence. Once the $i$-th user is decoded, the reconstructed signal $S_i(t)$ for this user is removed from the composite signal. The process will continue until all $K$ users are decoded. Due to the channel estimate errors or decision errors, $S_i(t)$ cannot be equal to $X_i(t)$ accurately, i.e., for the users who are decoded after user $i$, the interference from user $i$ cannot be perfectly removed. We denote by $\theta$ the fractional cancellation error [6], [8]–[11] of the $i$-th decoded user. Then the cancellation error due to user $i$ is $\theta P_i$, where $P_i$ is the received power of user $i$. Accordingly, the signal-to-interference-plus-noise ratio (SINR) of user $i$ can be expressed as [11]

$$\text{SINR}_i = \frac{P_i}{\sum_{j=1}^{i-1} P_j + \sum_{j=i+1}^{K} P_j + I_W}, \quad i = 1,2,\ldots,K \quad (1)$$

where all $\theta$'s are assumed to be the same for all users, denoted by $\theta$. This can be seen as a conservative case where $\theta$ is chosen as the maximum of all $\theta$ [8], [10], [11]. Typically, $0 \leq \theta \leq 1$.

In real DS-CDMA systems, there exist $E_{ij}$ requirements for users. In addition, the maximum transmission power of a mobile station is always limited. Thus, the maximum received power is also limited. Then, the constraints in DS-CDMA systems can be expressed as

$$E_{ij} r = \gamma_i; \quad i = 1,2,\ldots,K \quad (2)$$

$$0 \leq P_i \leq P_{\text{max}}; \quad i = 1,2,\ldots,K \quad (3)$$

where $\gamma_i$ is the $E_{ij}$ requirement of user $i$ with rate $r_i$, and $P_{\text{max}}$ is the maximum received power of $P_i$. (2) presents the $E_{ij}$ requirement of user $i$, and (3) is the constraint of the received power $P_i$ of user $i$.

Let $Y_i = W / (R_i \gamma_i)$. From (1) and (2), the following equations for received power requirements of users can be derived:

$$P_i = \frac{\theta + \gamma_i}{1 + \gamma_i} P_{\text{max}}; \quad i = 1,2,\ldots,K \quad (4)$$

$$P_i = \frac{1}{\gamma_i - \sum_{j=1}^{i-1} \gamma_j P_{j+1} + \sum_{j=i+1}^{K} (\theta + \gamma_j)(1 + \gamma_j)} \quad (5)$$

$$P_i = \frac{1}{\gamma_i - \sum_{j=1}^{i-1} \gamma_j P_{j+1} + \sum_{j=i+1}^{K} (\theta + \gamma_j)(1 + \gamma_j)} \quad (6)$$

Once a received power vector $P = [P_1, \ldots, P_r, \ldots, P_K]$ makes (2) and (3) be met under some decoding order, the system is feasible. Otherwise, if no received power vector $P = [P_1, \ldots, P_r, \ldots, P_K]$ can make (2) and (3) be met under all $K!$ possible decoding orders, the system is infeasible. Evidently, the computational complexity of examining the system feasibility directly by ESM is prohibitively high for a system with even non-trivial number of users. In the following, we propose an efficient approach for examining the feasibility of DS-CDMA systems with imperfect SIC. We theoretically prove that if (2) and (3) cannot be met under the decoding order obtained by the proposed approach, the system must be infeasible, i.e., (2) and (3) cannot be met under all possible decoding orders. Furthermore, under the obtained decoding order, the system is able to achieve the lowest outage probability among all decoding orders.

## III. EFFICIENT APPROACH FOR EXAMINING SYSTEM FEASIBILITY

In this section, we first present two theorems as well as their proofs, which form the base for our approach to examine the system feasibility. Next we describe the details of our approach. Finally we further prove that the decoding order obtained by our approach can achieve the lowest outage probability among all possible decoding orders.

**Theorem 1:** For a given decoding order, let $A$ and $B$ be the $m$-th and $n$-th decoded users respectively, where $1 \leq m < n \leq K$. Swapping only the orders of $A$ and $B$ and keeping the orders of other users unchanged in the decoding order, the $i$-th decoded user will have the same received power requirement as before, where $1 < i < m$ or $i > n$.

**Proof:** The following proof partially consults the proof of lemma 1 in [6].

We first consider the case where users $A$ and $B$ are neighbors in the decoding order, i.e., $1 < m = n-1 < K-1$, and next the general case of $1 < m = n-1 < K-1$. Let $P_i$ and $P_j$ be the $i$-th decoded user’s receiver power requirement before and after swapping the orders of $A$ and $B$ respectively. We can decompose this case ($1 < m = n-1 < K-1$) into the following two sub-cases.

1. **Sub-case of $1 < m = n-1 < K-1.$**

Let $U_i = \prod_{j=1}^{m-1} (\theta + Y_j) / (1 + Y_j)$. Before swapping the orders of $A$ and $B$, we have

$$U_i = \frac{\theta + Y_j}{1 + Y_j} \prod_{j=1}^{m-1} \left( \frac{\theta + Y_j}{1 + Y_j} \right) \prod_{j=m+1}^{n-1} (\theta + Y_j) / (1 + Y_j) \quad (7)$$

After swapping the orders of $A$ and $B$, we have

$$U_i = \frac{\theta + Y_j}{1 + Y_j} \prod_{j=1}^{m-1} \left( \frac{\theta + Y_j}{1 + Y_j} \right) \prod_{j=n+1}^{K-1} (\theta + Y_j) / (1 + Y_j) \quad (8)$$

For the $i$-th decoded user, where $1 < m < n$, we have

$$U_i = \frac{\theta + Y_j}{1 + Y_j} \prod_{j=1}^{m-1} (\theta + Y_j) / (1 + Y_j) = U_i \quad (11)$$

For the $i$-th decoded user, where $i > n$, we have

$$U_i = \prod_{j=1}^{m-1} (\theta + Y_j) / (1 + Y_j) \prod_{j=n+1}^{K-1} (\theta + Y_j) / (1 + Y_j)$$

$$= \prod_{j=1}^{m-1} (\theta + Y_j) / (1 + Y_j) \prod_{j=n+1}^{K-1} (\theta + Y_j) / (1 + Y_j)$$

Accordingly,

$$\sum_{j=m+1}^{n-1} U_j = U_i + U_j - U_j - U_j = 0$$

By (5), after swapping the orders of $A$ and $B$, we can
derive:
\[
\hat{P}_i = \frac{I_W}{Y_i - \sum_{j \neq i}^K U_j} = \frac{I_W}{Y_i - \sum_{j \neq i}^K U_j} = P_i
\]  
(14)

This means that the first decoded user keeps its received power requirement unchanged.

Next, by (4), after swapping the orders of A and B, for the i-th decoded user, where i < m or i > n, we have:
\[
P_i = P_i \cdot U_i' = P_i \cdot U_i' = P_i
\]  
(15)

This means that the i-th decoded user, where i < m or i > n, keeps its received power requirement unchanged.

(2) Sub-case of 1 ≤ m = n ≤ K − 1.

Let \( V_{ij} = \prod_{1}^{i-1}(1 + Y_j)/(1 + Y_j) \). Before swapping the orders of A and B, we have
\[
V_s = \frac{(1 + Y_{\alpha(s)}) \prod_{1}^{i-1}(1 + Y_j)/(1 + Y_j)}{(1 + Y_{\alpha(s)}) \prod_{1}^{i-1}(1 + Y_j)/(1 + Y_j)} = V_s
\]  
(16)

After swapping the orders of A and B, for the i-th decoded user, where i < m and i > n, we have \( V'_s = V_s' \), and
\[
V'_s = \frac{(1 + Y_{\alpha(s)}) \prod_{1}^{i-1}(1 + Y_j)/(1 + Y_j)}{(1 + Y_{\alpha(s)}) \prod_{1}^{i-1}(1 + Y_j)/(1 + Y_j)} = V'_s
\]  
(17)

By (6), after swapping the orders of A and B, we can derive:
\[
\hat{P}_k = \frac{I_W}{Y_k - \sum_{j \neq k}^K U_j} = \frac{I_W}{Y_k - \sum_{j \neq k}^K U_j} = P_k
\]  
(21)

Next, by (4), after swapping the orders of A and B, for the i-th decoded user, where i < m or i > n, we have:
\[
P_i = P_i \cdot V_i' = P_i \cdot V_i' = P_i
\]  
(22)

This also means that the i-th decoded user, where i < m or i > n, keeps its received power requirement unchanged.

To extend the above analysis to the general case where 1 ≤ m < n ≤ K, we can recursively swap the orders of A and A′s neighbor decoded immediately after A and swap the orders of B and B′s neighbor decoded just before B respectively, until we have swapped the orders of A and B. Above two sub-cases, we can conclude that Theorem 1 is true.

Based on Theorem 1, we have another theorem as follows.

**Theorem 2:** The sufficient and necessary condition for a system with \( K \) active users to be feasible is that (2) and (3) must be met under the decoding order of \( Z_1, Z_2, \ldots, Z_k \), where \( Z_i, (i = 1, 2, \ldots, K) \) are defined as
\[
Z_i = P^m_i (l + Y) = P^m_i [1 + W/(R_i)], \quad i = 1, 2, \ldots, K
\]  
(23)

**Proof:** For the sufficient condition, it is obvious. Let us focus on the necessary condition.

Under a given decoding order, we define the decoding order vector as \( Z = [Z_1, \ldots, Z_i, \ldots, Z_k] \), where the element \( Z_i = P^m_i (l + Y) \) is associated with the i-th decoded user in the decoding order.

Suppose that a system with \( K \) users under a specific decoding order is feasible but the corresponding decoding order vector \( Z = [Z_1, \ldots, Z_i, \ldots, Z_k] \) has its elements not in descending order, i.e. there exist user \( l \) and its immediate subsequent user \( (l + 1) \) with \( Z_l < Z_{l+1} \). Let \( P = [P_1, P_2, \ldots, P_k] \) be the corresponding received power vector of the K users. We examine the new received power vector after swapping the orders of users \( l \) and \( (l + 1) \) in the following three cases.

(1) \( l = 1 \). After swapping the orders of users 1 and 2, the new decoding order vector is \( \tilde{Z} = [Z_2, \ldots, Z_i, \ldots, Z_k, \ldots, Z_k] \), and the corresponding received power vector is \( \tilde{P} = [P_2, P_3, \ldots, P_k, \ldots, P_k] \). By Theorem 1, before and after swapping users 1 and 2, the i-th decoded user, where \( i ≥ 3 \), has the same received power requirement. Accordingly, we have
\[
\hat{P}_i = \frac{P_i (l + Y)}{(1 + Y)} ≤ \frac{P_i (l + Y)}{(1 + Y)} = \frac{P_i}{P_{\max}} \quad i = 3, 4, \ldots
\]  
(24)

Thus, (2) and (3) are still met under the new decoding order after swapping.

(2) \( l = K - 1 \). After swapping the orders of users \( (K - 1) \) and \( K \), the new decoding order vector is \( \tilde{Z} = [Z_1, \ldots, Z_i, \ldots, Z_k, Z_{i+1}, Z_{i+2}, \ldots, Z_k] \), and the corresponding received power vector is \( \tilde{P} = [P_1, P_2, \ldots, P_{i+1}, P_{i+2}, \ldots, P_k] \). By Theorem 1, before and after swapping the decoding orders of users \( (K - 1) \) and \( K \), the i-th decoded user, where \( i ≤ K - 2 \), has the same received power requirement. Accordingly, we have
\[
\hat{P}_i = \frac{P_i (l + Y_{

Thus, (2) and (3) are still met under the new decoding order after swapping.

(3) \( 1 ≤ l < K - 1 \). After swapping the orders of users \( l \) and \( (l + 1) \), we have the new decoding order vector \( \tilde{Z} = [Z_1, \ldots, Z_i, \ldots, Z_{(l + 1)}, Z_{(l + 2)}, \ldots, Z_k] \), and the corresponding received power vector is \( \tilde{P} = [P_1, P_2, \ldots, P_{(l + 1)}, P_{(l + 2)}, \ldots, P_k] \). Again by Theorem 1, both of the first decoded user (user 1) and the last decoded user (user \( K \)) have their received power requirements unchanged. In a similar way as case 1 or case 2, (2) and (3) are still met under the new decoding order after swapping.

By recursively applying the operations in above three cases until all elements in the decoding order vector \( Z \) are in descending order, (2) and (3) are always met under the new decoding order. Thus, Theorem 2 is true.

In this paper, we denote by \( ZD \) the decoding order according to the decoding order of \( Z_1, Z_2, \ldots, Z_k \) and our approach for examining the system feasibility can be formulated as follows.

First, we calculate \( Z_i, (i = 1, 2, \ldots, K) \) and determine the decoding order of \( ZD \) according to the decoding order of \( Z \).

Second, the received power requirements of users under the decoding order of \( ZD \) are calculated according to (4), (5) and (6).

Third, we check whether (2) and (3) can be met under the decoding order of \( ZD \).

By Theorem 2, if (2) and (3) cannot be met under the decoding order of \( ZD \), the system must be infeasible; otherwise, the system is feasible. In this way, we can examine the system feasibility by checking only one decoding order, i.e., the decoding order of \( ZD \) instead of directly using ESM to check every decoding order one by one.

Based on Theorem 2, we have the following corollary.
Corollary 1: Under the decoding order of ZD, the system can achieve the lowest outage probability among all possible decoding orders.

Proof: By Theorem 2, once the system is feasible, (2) and (3) must be met under the decoding order of ZD, even if (2) and (3) may not be met under some other decoding orders. Thus, we can assert that the system under the decoding order of ZD can achieve the lowest outage probability among all possible decoding orders. ■

To intuitively appreciate the reasonability of the decoding order of ZD in terms of system feasibility, we discuss the following two cases.

1. All K users have the same rate and P Ej requirement, i.e., all \( Y_r = W/(R_Y) \) are identical. In this situation, the decoding order of ZD corresponds to the descending order of Pmax. When a user is decoded later, it will experience less interference and its received power requirement will be smaller according to (1) and (2). Hence, it is reasonable that all K users are decoded according to the descending order of Pmax such that the system is most likely to be feasible. Furthermore, if all users have the same maximum transmission power, the decoding order of Pmax corresponds to the descending order of users’ channel gains.

2. All K users have the same P Ej requirement. In this situation, the decoding order of ZD corresponds to the descending order of \( Y_r = W/(R_Y) \). According to (1) and (2), the greater \( Y_r = W/(R_Y) \) is, the lower the corresponding SINR requirement is. At the same time, the earlier a user is decoded, the more interference it will experience. Hence, it is reasonable that all K users are decoded according to the descending order of \( Y_r = W/(R_Y) \) such that the system is most likely to be feasible. Moreover, if all users have the same rate Ej requirement, the descending order of \( Y_r = W/(R_Y) \) corresponds to the ascending order of R.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we conduct simulation experiments to illustrate the performance of the proposed approach in terms of two aspects: (1) computational complexity of examining the system feasibility; and (2) system outage probability.

The channel gain of a user is composed of path loss and shadowing as [12], i.e.,

\[ h = \frac{1}{PL(d)} e^{\beta + \xi} \]  \hspace{1cm} (28)

where \( \beta = \ln 10/10; \xi \) is a gaussian random variable with zero mean and standard deviation \( \sigma \); \( e^{\xi} \) represents the shadowing effect, which is modeled as a log-normal distribution; and \( PL(d) \) is the path loss model given as [12].

\[ PL(d)[dB] = 129.4 + 35.2 \log_{10}(d) \]  \hspace{1cm} (29)

where \( d \) is the range in kilo-meters between a user and the BS. In our simulation experiments, the path losses of all users are uniformly distributed over \((-15, 15) \) dB with the center representing the average value of all these path losses in the corresponding random sample.

In the experiments, we adopt typical system parameters listed in Table I, part of which are the same as those in [12].

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>SYSTEM PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum transmission power [W]</td>
<td>0.25</td>
</tr>
<tr>
<td>System Bandwidth [MHz]</td>
<td>3.84</td>
</tr>
</tbody>
</table>

A. Computational Complexity of Examining the System Feasibility

The process of checking each decoding order has the same computational complexity, which includes all the operations that are involved in (4), (5) and (6), where the received power requirements are calculated under this decoding order, and that are involved in (2) and (3), where the constraints are examined. Hence, the number of decoding orders involved in examining the system feasibility corresponds to the computational complexity. In the worst case, ESM needs to check all \( K! \) decoding orders to identify that the system is feasible or infeasible, so that the computational complexity of ESM is \( O(K!) \). In contrast to ESM, the proposed approach for examining the system feasibility involves only one decoding order, i.e., the decoding order of ZD, so that the computational complexity of the proposed approach is only \( O(1) \), which is significantly less than that of ESM. We will illustrate the computational complexity of different methods in terms of the number of involved decoding orders.

Fig. 1 shows the average number of decoding orders involved in ESM and the proposed approach for examining the system feasibility as a function of average maximum SNR with different fractional cancellation errors. In addition, the number of users varies from 6 to 7 and the rates of users are randomly chosen in the discrete data rate set in Table I. It is clear that ESM involves a big number of decoding orders and the number increases rapidly as the user number. In contrast to ESM, the number of decoding order involved in the proposed approach is always just one. Especially, when the fractional cancellation error \( \theta \) is larger and/or the number of users is bigger, the difference of the computational complexity between ESM and the proposed approach is more distinct. This is due to the fact that when the fractional cancellation error is larger and/or the number of users is bigger, the probability that the system is infeasible is higher, thus the saving of computational complexity under ZD is more significant.

B. System Outage Probability

Next, we investigate the system outage probability under ZD and several typical decoding orders. Let RD represent the decoding order according to the descending order of rates, RA represent the decoding order according to the ascending order of rates, and ORN represent the randomly selected decoding order among all possible decoding orders. Fig. 2 shows the outage probabilities of the system under ZD, RD, RA and ORN as a function of average maximum SNR. In addition, the number of users is fixed as 6 and the rates are randomly chosen in the discrete data rate set in Table I. It is clear that the outage probability under ZD is always lower than that under all other decoding orders. Especially, the smaller the fractional cancellation error \( \theta \) is, the more distinct the outage probability difference between ZD and all other decoding orders is. This is due to the fact that when the fractional cancellation error \( \theta \) is smaller, the system is more likely to be feasible. Hence, by Theorem 2, (2) and (3) must be more likely to be met under ZD even if (2) and (3) cannot
be met under some other decoding orders, thus the outage probability difference is more evident.

In above experiments, even though the benefit in terms of outage probability difference is not significant, we have theoretically proved that the system feasibility can be efficiently examined by checking only the decoding order of \(\text{ZD}\). It can be deemed as an additional merit that the system under the decoding order of \(\text{ZD}\) is able to achieve the lowest outage probability in the mean time.

V. CONCLUSION

In this paper, we have proposed an efficient approach for examining the feasibility of DS-CDMA systems with imperfect SIC, where the received power is constrained. We can examine the system feasibility under only the decoding order obtained by the proposed approach. The proposed approach can bring gains in two ways: (1) significant lower computational complexity of examining the system feasibility, which will benefit the quick decision of admission control and/or scheduling in DS-CDMA systems; (2) lowest outage probability, i.e., under the obtained decoding order, the system is able to achieve the lowest outage probability among all possible decoding orders. Our findings and designs in this paper can be applied in QoS mechanisms (such as admission control and/or scheduling) designs in DS-CDMA systems.

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