Survey on Non-orthogonal Multiple Access with SIC and Related Topics in Scheduling

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***Abstract*—The report shows progress of literature survey on the physical and MAC layer techniques for non-orthogonal multiple access (NOMA). The content of the report focus on the technique of successive interference cancellation (SIC) in OFDM system. In section II shows different capacity model of SIC and in section III shows scheduling problems in different scenarios.**

I. Introduction

The project aims on investigating in non-orthogonal multiple access (NOMA) in ultra-high density network. The report is about the progress of literature sruvey on the physical and MAC layer techniques for successive interference cancellation (SIC). In the following, we first briefly describe some of the papers surveyed, and then we organize our findings into *physical layer* and *MAC layer* aspects in Section II and Section III respectively.

Briefly, in [1], the authors compare the performance between orthogonal frequency-division multiple access (OFDMA) and NOMA. They in particular investigate successive interference cancellation (SIC) and state that SIC receivers should follow the rule that the optimal order for decoding is in the order of the increasing $\frac{|h|^2}{N}$. Also, a NOMA/Multiple-Input Multiple-Output (MIMO) scheme is proposed to achieve further capacity gain [7]. In [2], the authors investigate the enhancement of the cell-edge user throughput by using SIC in the cellular downlink. They propose an optimization method that can balance the throughput of cell-edge users and interior users. The work in [3] is the extension of [2], where the authors investigate the use of FFR and weighted PF-based multi-user scheduling with SIC in the cellular downlink. They show that NOMA can help achieve user fairness.

Related work in [4] not only considers the ideal channel capacity but also analyzes SIC performance with respect to modulation schemes and packet error rate (PER). A resource allocation algorithm is proposed to leverage the spatial gain and the simulation results show that proposed algorithm using NOMA with SIC achieves more than 100 percent throughput gain comparing OFDMA. In [5], the authors investigate SIC and proposed an iterative SIC receiver architecture with combined pilot/date based channel estimation for efficient decoding of NOMA signals. The simulation results show iterative SIC receivers reach low PER with weak SNR under a reasonable complexity.

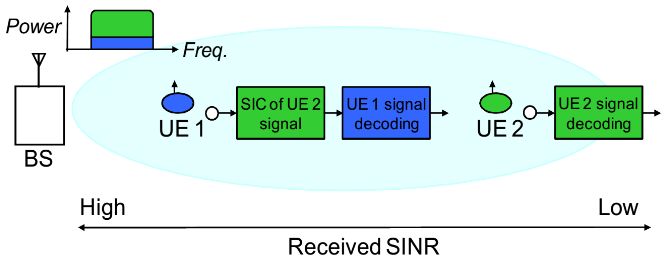

Fig. 1: Two-user SIC in the downlink

II. PHY Layer Aspects

To allow non-orthogonal access from multiple users over the same radio resource, successive interference cancellation (SIC) or superposition coding has been popularly considered in the literature [1]–[3].

A. SISO SIC receiver

To understand how SIC works, take the two-user downlink communication in Fig. 1 as an example. The transmitted signal from the base station is a linear combination of the signals intended for UE1 and UE2. To decode individual signals, SIC needs to be performed at each receiving UE. The optimal order for decoding is the order of the increasing channel gain normalized by the noise and inter-cell interference power. Assuming that the channel gain of UE1 is better than UE2, if UE2 can decode its signal, then UE1 must also be able to decode the UE2 signal. Therefore, as shown in Fig. 1, UE1 first decodes the signal of UE2 and then decodes its signal after the decoded UE2 signal has been subtracted. For UE2, it can simply go ahead and decode its own signal without decoding the signal for UE1 first. The case for SIC by K UEs can be performed similarly, and ideally for any UE the optimal decoding is to remove the interference coming from UEs with worse channel gains. As shown in [1], the achievable rate $R_b^{(\mathrm{sic})}(k)$ for UE k in resource b can be represented as follows:

$$R_b^{(\mathrm{sic})}(k) = W_b \log_2 \left(1 + \frac{|h_{k,b}|^2 P_{k,b}}{\sum\limits_{\substack{i=1 \\ \frac{|h_{k,b}|^2}{N_{k,b}} < \frac{|h_{i,b}|^2}{N_{i,b}}}}^{K} |h_{k,b}|^2 P_{i,b} + W_b N_{k,b}} \right), \tag{1}$$

where $|h_{i,b}|^2$ is channel gain between UE i and the base station, W_b is the bandwidth of resource b, $P_{i,b}$ is the transmission power allocated to UE i, and $N_{i,b}$ is the noise and inter-cell interference power for UE i. Equation 1 shows a simple version of SIC reception model, and the work in [6] investigate the design of a SISO SIC receiver operating on OFDM system considering ICI cause by time variations in channel.

B. MIMO SIC

For system beyond LTE-Advanced in the future, successive interference canceller (SIC) in the cellular multiple-input multiple-output (MIMO) is an important issue.

We consider investigation of NOMA with SIC in the cellular MIMO system. The idea is to implement SIC to signals within a single beam controlled by the beamforming (precoding) matrix. In [7], the authors propose intra-beam superposition coding of a multiuser signal at the transmitter and the spatial filtering of inter-beam interference followed by the intra-beam SIC at the user terminal receiver. The intra-beam SIC cancels out the inter-user interference within a beam. According to [7], the channel after the spatial filtering is a degraded SISO channel, and the equivalent normalized channel gain of user k scheduled in frequency block b on beam i can be formulated as follows:

$$g_{k,b,i} = \frac{|\mathbf{v}_{k,b,i}^H \mathbf{H}_{k,b} \mathbf{m}_{b,i}|^2}{\sum\limits_{i' \in I, i' \neq i} P_{i'} |\mathbf{v}_{k,b,i}^H \mathbf{H}_{k,b} \mathbf{m}_{b,i'}|^2 + \mathbf{v}_{k,b,i}^H E[\mathbf{w}_{k,b} \mathbf{w}_{k,b}^H] \mathbf{v}_{k,b,i}} \tag{2}$$

In equation 2, $\mathbf{v}_{k,b,i}$ denotes the spacial filter vector, in [7], it is is calculated based on the minimum mean squared error (MMSE) criteria. $\mathbf{H}_{k,b}$ denotes the N $\times$ M-dimensional channel matrix between the base station and user k at frequency block b. $\mathbf{m}_{b,i}$ denotes the transmitter beamforming vector. $\mathbf{w}_{k,b}$ denotes the receiver noise plus inter-cell interference vector at frequency block b, and P_i is the transmission power of beam i. Therefore, we can apply intra-beam SIC to received signal in the same way by equation 1.

In practice, it might not be possible to achieve perfect interference cancellation. The authors in [4] have show simulation results for SIC with respect to modulation schemes and SNR difference as given in Fig. 2. All points enclosed in the upper right area of each curve are in the desired operating region with PER $\leq 10^{-2}$. Table I further shows the relationship between modulation and SNR for three marked points in the figure. We can find that the simulation result does not strictly follow (1). For example, if the SNR of U1 becomes 8 times

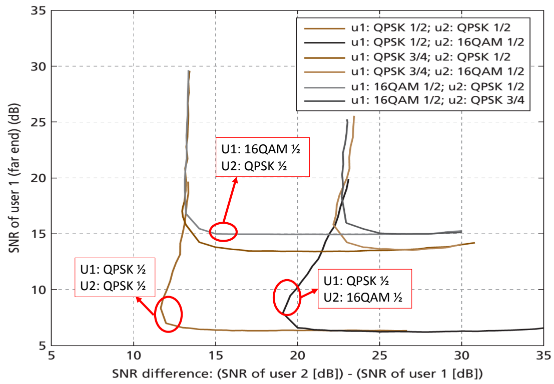

Fig. 2: Modulation and PER vs. SNR difference

TABLE I: Modulation curve in Fig. 2

U1 Modulation	U2 Modulation	SNR of U1	SNR Diff
QPSK 1/2	QPSK 1/2	6-15	12-20
QPSK 1/2	16QAM 1/2	6-15	≥ 20
16QAM 1/2	QPSK 1/2	$\geq$15	12-20

(i.e. 9 dB) larger, the modulation of U1 can upgrade from QPSK to 16QAM, which has only 2 times larger capacity. Fig. 2 motivates our further investigation on the practical performance of SIC for MAC layer design.

III. MAC Layer Aspects

To leverage the benefits of NOMA, MAC layer techniques such as resource allocation, scheduling, and power control need to be properly redesigned for performance optimization. In the following, we describe two related work for allocating resources to NOMA users.

A. Two-user resource allocation

The authors in [4] consider the problem of choosing the best pair of UEs for sharing each resource unit. An algorithm called variable multi-user resource allocation as shown in Algorithm 1 is proposed. Specifically, UEs are sorted in the descending order of their channel gains. For each candidate UE, the algorithm first finds the other UE that can use the same resource based on the simulation model in Fig. 2. The set of UEs that can pair with the candidate UE is obtained as group $\mathcal{A}$. Then, group $\mathcal{B}$ is obtained from $\mathcal{A}$, where the multi-user data rate $R_b^{(\mathrm{sic})}(z)$ of the far user z should reach at least half of its single-user data rate $R_b(y)$. Finally, group $\mathcal{C}$ is obtained from group $\mathcal{B}$ by the rule of fair scheduling. The algorithm allocates the resource to the pair (x, y) whose sum rate is the highest in group $\mathcal{C}$.

B. Maximizing system throughput for multi-user scenarios

In [2], the authors investigate an optimization problem that can dynamically control the worst data rate and the maximum data rate in the cellular system. Ideally, the total user sum rate is maximized when each resource is assigned to a user with the highest signal-to-interference plus noise power ratio

Algorithm 1 Variable multi-user resource allocation algorithm

Sort users in descending order by their channel gains
for each user x in the sorted list **do**
  $\mathcal{A}$ = $\{(x,y)|(x,y)$ both fulfill NOMA constraint with y being the far user$\}$
  $\mathcal{B}$ = $\{(x,y)|\ (x,y) \in \mathcal{A}$ and $R_b^{(\text{sic})}(z) \geq \frac{1}{2}R_b(z)$, where $z = \arg\min_{i=x,y}|h_i|^2\}$
  $\mathcal{C}$ = $\{(x,y)|(x,y) \in \mathcal{B}$ and y is less scheduled$\}$
  Select $(x,y) \in \mathcal{C}$ that has the highest sum rate
  Allocate one resource to (x,y)
end for

(SINR) among candidate users. Specifically, if there are K users and B resources, the maximum sum rate, R_{max}, can be represented as

$$R_{\text{max}} = \sum_{b=1}^{B} W_b \log_2\left(1 + \frac{\max_k\left(\frac{|h_{k,b}|^2}{N_{k,b}}\right)P_{k,b}}{BW_b}\right). \quad (3)$$

Notice that base station can transmit maximum power P/B per resource unit.

Based on (1) and (3), the problem to maximize the worst user data rate with total rate constraint is written as

$$\begin{aligned} \text{maximize} \quad & \min_{k\in K} R^{(\text{sic})}(k) \\ \text{subject to} \quad & P_{k,b} \geq 0, \forall k,b, \\ & \sum_{k=1}^{K} P_{k,b} = P/B, \forall b, \\ & \sum_{k=1}^{K} R^{(\text{sic})}(k) \geq \alpha R_{\text{max}}, \end{aligned} \quad (4)$$

where $R^{(\text{sic})}(k) = \sum_{b=1}^{B} R_b^{(\text{sic})}(k)$. The parameter α is adjustable, where a larger value of α favors the total user rates while a smaller value of α favors user fairness. For example, if $\alpha < 1$, the base station does not need to fulfill the strict constraint of R_{max} and can allocate resources to other users.

Problem (4) is not a convex optimization problem; therefore, the solution obtained using the interior-point method depends on the initial setting of parameters $P_{k,b}$. In view of (3), the authors use the following for initial setting of $P_{k,b}$ in the evaluation:

$$P_{k,b} = \begin{cases} \frac{P}{B}, & k = \arg\max_i\left(\frac{h_{i,b}}{N_{i,b}}\right) \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

Still, due to the complexity of the problem, the solution of (4) obtained by the interior point method through (5) is local optimal but not global optimal. Further investigation on formulation and optimization of multi-user resource allocation is needed.

C. Enhance fairness in FFR with modified PF scheduling

The study in [3] aims to let cell-edge users have better network experience which is similar to the work in [2]. They propose scheduling algorithm extends the concept of fractional frequency reuse (FFR) and weighted proportional fair (PF)-based multiuser scheduling to nonorthogonal access with a successive interference cancellation (SIC) in the cellular downlink.

A typical method, soft FFR, the overall system transmission bandwidth is divided into two parts: a frequency band with priority given to cell-edge users ($\mathcal{B}_{\text{edge}}$) and that with priority given to cell-interior users ($\mathcal{B}_{\text{inner}}$). The bandwidth for the edge band is assumed to be 1/3 of the overall system transmission bandwidth.

The average user throughput of user k per frequency block is defined as

$$T(k;t+1) = \left(1 - \frac{1}{t_c}\right)T(k;t) + \frac{1}{t_c}\left(\frac{1}{B}\sum_{b=1}^{B} R_b^{(\text{sic})}(k;t)\right), \quad (6)$$

where t denotes the time index and t_c defines the time defines the time horizon in which we want to achieve fairness. Obviously, the larger t_c, the less stringent the fairness constraint, and thus longer delays start appearing between successive transmissions to the same user.

In FFR, the scheduling metric is affected by the frequency block access policy. The sets of users categorized into cell-edge and cell-interior user groups are denoted as $\mathcal{K}_{\text{edge}}$ and $\mathcal{K}_{\text{inner}}$ respectively. By modifying original PF-based multi-user scheduling, the resource access policy applies the following selecting criteria:

$$f_b(S) = \prod_{k\in S}\left(1 + \frac{\alpha_b(k)R_b^{(\text{sic})}(k|S;t)}{(t_c-1)T^{\gamma}(k;t)}\right) \text{and} \quad (7)$$

and the product of the average user throughput among users is maximized by selecting user set $\mathcal{S}_b$ by

$$\mathcal{S}_b = \arg\max_s f_b(\mathcal{S}) \quad (8)$$

where S is the schedule set and $\gamma(0 \leq \gamma)$ is the weighting factor designed to achieve better user fairness. Here, soft priority access coefficient α denotes whether or not the users at the edge can access the inner band or interior users can access the edge band. The coefficient is defined as follows,

$$\alpha_b(k) = \begin{cases} \alpha_{\text{edge}}, & b \in \mathcal{B}_{\text{inner}}, k \in \mathcal{K}_{\text{edge}} \\ \alpha_{\text{inner}}, & b \in \mathcal{B}_{\text{edge}}, k \in \mathcal{K}_{\text{inner}} \\ 1, & \text{otherwise,} \end{cases} \quad (9)$$

To determine the transmission power in this case, equation 7 is approximated as

$$f_b(\mathcal{S}) = \sum_{k\in\mathcal{S}} \frac{\alpha_b(k)R_b(k|S;t)}{T^{\gamma}(k;t)} \quad (10)$$

Which is a weighted sum of the instantaneous user throughput. Therefore, for given candidate scheduling policy, the metric can be maximized by water-filling power allocation method.

By the scheduling method introduced in previous works, the performance of geometric mean user throughput of Non-orthogonal access with SIC networks is better than OFDM networks. However the performance of PF scheduler in NOMA-SIC access networks is not evaluated and remains unclear.

D. Scheduling Links considering user demands

Similar to the work of [8], considering the difference of demands for users in cellular system, a new scheduling algorithm is needed. Assume that there are $|\mathbf{V}|$ users randomly distributed in the Euclidean space and a single base station in the middle, each user send requests of QoS at the beginning of each schedule round (length $|\mathbf{T}|$). The scheduling problem is to maximized the number of user served and meet the QoS requirement at the same time. The problem can be formulated as:

$$\max \sum_{k \in \mathbf{V}} X_k \tag{11}$$

where X_k is the binary variable denotes whether or not user k is served. The QoS requirement for k is Q_k, and therefore we have constraints:

$$\frac{1}{|\mathbf{V}|} \sum_{t \in \mathbf{T}} \sum_{b \in \mathbf{B}} X_k R_k(k|S_b;t) \geq Q_k, \forall k \in \mathbf{V}. \tag{12}$$

IV. Conclusion

We've surveyed models for NOMA with SIC in OFDM system form the prior work which covers the design of SIC receiver, single antenna SIC Capacity model, MIMO-SIC downlilnk model and topics subject to resource allocation and scheduling considering user fairness in NOMA with SIC. However, according to the scope of project purposed, there are some part remains unclear. For example, inter-cell interference is neglected, and we have not found sufficient literature about uplink MIMO-SIC model and coordinate muti-point (COMP) access model.

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