

# Average Throughput Improvements by Using NOMA in CRE-Based Heterogeneous Networks

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**Abstract**—In heterogeneous networks (HetNets), Cell Range Expansion (CRE) improves 5-percentile user throughput by offloading user equipment (UEs) from macro base stations (macro-BSs) to pico base stations (pico-BSs) using a cell selection offset (CSO). However, CRE increases the number of UEs connected to pico-BSs, which causes radio resource sharing among pico-cell UEs and degrades the throughput of native pico-cell UEs that originally achieved higher throughput. As a result, the overall average user throughput decreases. This paper proposes the application of Non-Orthogonal Multiple Access (NOMA) to pico-BSs in CRE-based HetNets. In the proposed scheme, native pico-cell UEs and CRE UEs are paired for NOMA transmission at pico-BSs, and Orthogonal Multiple Access (OMA) or NOMA is adaptively selected based on proportional fair (PF) scheduling metrics. Through system-level simulations, the average user throughput and 5-percentile user throughput are evaluated. Simulation results show that the proposed scheme mitigates the average throughput degradation caused by CRE while maintaining the 5-percentile user throughput improvement achieved by CRE. Furthermore, the sensitivity of the proposed scheme to imperfect successive interference cancellation (SIC) is evaluated. The results suggest that a clear NOMA gain can be obtained when the residual interference factor is below 0.1, whereas at  $\beta = 0.1$ , the performance is nearly identical to the fixed-CRE OMA.

**Keywords**—mobile communications, heterogeneous networks, cell range expansion, non-orthogonal multiple access, proportional fair

## I. INTRODUCTION

Heterogeneous networks (HetNets), which consist of macro base stations (macro-BSs) and pico base stations (pico-BSs), are considered an effective approach for improving the system throughput of future mobile communication systems [1]. Fig. 1 illustrates the considered HetNet environment. In HetNets, Cell Range Expansion (CRE) is used to offload UEs from macro-BSs to pico-BSs by applying cell selection offsets (CSOs) to pico-BSs [2], [3]. CRE mainly improves 5-percentile user throughput. To further improve the trade-off between average and cell-edge user throughput, an adaptive CSO control scheme that applies different CSO values depending on UE channel conditions has also been proposed [12].

However, CRE also increases the number of UEs connected to pico-BSs. When CRE UEs are newly offloaded to pico-BSs, the radio resources of pico-BSs must be shared by both native pico-cell UEs and CRE UEs. As a result, the resource allocation to native pico-cell UEs, which originally tend to have higher throughput, decreases. This reduction in the throughput of native pico-cell UEs can reduce the overall average user throughput, although CRE improves the 5-percentile user throughput.

On the other hand, Non-Orthogonal Multiple Access (NOMA) has also attracted attention as a means of increasing

user throughput for 5G/beyond-5G mobile communication systems [4]. NOMA enables multiple UEs to simultaneously share the same radio resources. In downlink power-domain NOMA, higher transmission power is allocated to the far UE, while the near UE performs SIC to remove the far-UE signal before decoding its own signal. Therefore, UEs with significantly different channel conditions, such as near and far UEs, are suitable candidates for power-domain NOMA pairing.

Several studies have investigated PF-based user pairing, scheduling, and power allocation schemes for NOMA systems [5]–[7]. However, NOMA does not always outperform OMA under practical conditions because its gain depends on UE conditions, channel environments, and the degradations of modulation and coding schemes caused by power-domain multiplexing. Therefore, selectively applying OMA or NOMA based on PF scheduling metrics is important for improving system throughput.

In this paper, we propose applying NOMA to pico-BSs in CRE-based HetNets. Native pico-cell UEs and CRE UEs connected to the same pico-BS are treated as near and far UEs, respectively, and the scheduler adaptively selects OMA or NOMA by comparing their PF metrics. Through system-level simulations, we evaluate the average user throughput, 5-percentile user throughput, NOMA selection ratio, and sensitivity of the proposed scheme to imperfect SIC. A residual interference factor is introduced to identify the range in which NOMA remains effective.

The remainder of this paper is organized as follows. Section II describes the system model and the proposed NOMA application scheme using PF-based OMA/NOMA selection. Section III presents the simulation conditions and results. Finally, Section IV concludes this paper.

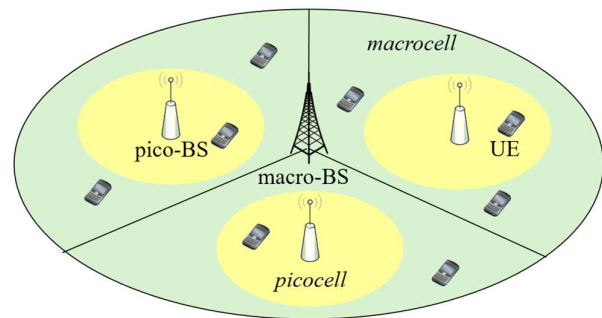


Fig. 1. HetNet environment.

## II. SYSTEM MODEL AND PROPOSED SCHEME

### A. CRE-based HetNets

Fig. 2 illustrates the CRE-based HetNet considered in this paper. In conventional cell selection, each UE connects to the base station with the highest downlink reference-signal received power (RSRP). In CRE, a cell selection offset (CSO) is added to the downlink RSRP from the pico-BS. Thus, a UE selects the pico-BS when the biased RSRP of the pico-BS exceeds the RSRP of the macro-BS.

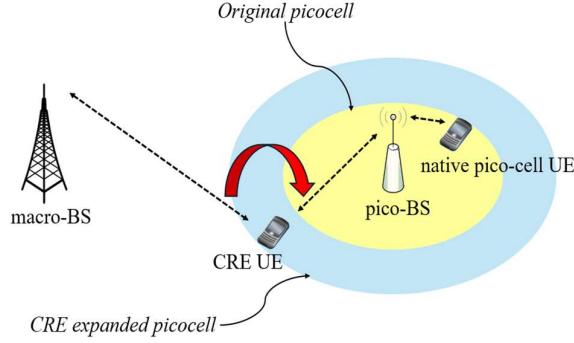


Fig. 2. CRE-based HetNet.

As a result, UEs outside the original pico-cell coverage are offloaded from the macro-BS to the pico-BS and are referred to as CRE UEs in this paper. Although CRE improves 5-percentile user throughput by offloading cell-edge UEs, it increases the number of UEs connected to pico-BSs. Consequently, native pico-cell UEs and CRE UEs share the radio resources of pico-BSs in OMA systems, which reduces the radio resources allocated to native pico-cell UEs and may degrade the overall average user throughput.

### B. NOMA Pairing of Native Pico-Cell UEs and CRE UEs

NOMA enables multiple UEs to share the same radio resource by using power-domain multiplexing and SIC. In downlink NOMA, the pico-BS superposes the signals of multiple UEs with different power levels. A higher transmission power is allocated to the far UE with poorer channel conditions, while a lower transmission power is allocated to the near UE with better channel conditions. The near UE first decodes and cancels the far UE signal by SIC and then decodes its own signal.

Fig. 3 shows the NOMA pairing considered in this paper. In the proposed scheme, NOMA pairing is performed between a native pico-cell UE and a CRE UE connected to the same pico-BS. Since the native pico-cell UE generally has higher received SINR than the CRE UE, the native pico-cell UE is treated as the near UE, whereas the CRE UE is treated as the far UE. By allowing these UEs to share the same radio resource, the proposed scheme aims to mitigate the average throughput degradation caused by increased resource sharing at pico-BSs in CRE-based HetNets.

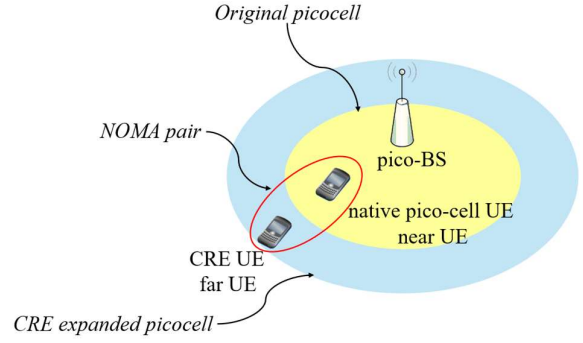


Fig. 3. NOMA pairing of native pico-cell UE and CRE UE.

### C. PF-based OMA/NOMA Selection

In the proposed scheme, OMA and NOMA are adaptively selected based on the proportional fair (PF) scheduling metric. First, a UE is selected for each radio resource according to the conventional PF scheduler. When the selected UE is a native pico-cell UE, it is treated as a near UE, and CRE UEs connected to the same pico-BS are evaluated as far-UE candidates for NOMA multiplexing. If a suitable far UE and power allocation ratio are found, the selected native pico-cell UE and the CRE UE are multiplexed on the same radio resource by downlink power-domain NOMA. Otherwise, the selected UE is scheduled by OMA.

Let  $\gamma_k(t)$  denote the received SINR of UE  $k$  when the full transmission power is allocated to the UE. In downlink power-domain NOMA, a native pico-cell UE and a CRE UE connected to the same pico-BS are multiplexed on the same radio resource. Let  $n$  and  $f$  denote the near UE and far UE, respectively. The transmission power ratio allocated to the near UE is denoted by  $\alpha$ , while that allocated to the far UE is  $1 - \alpha$ . Assuming perfect SIC at the near UE, the received SINRs of the near UE and far UE in NOMA are given by

$$\gamma_{near}^{NOMA}(t) = \alpha \gamma_{near}(t) \quad (1)$$

$$\gamma_{far}^{NOMA}(t) = \frac{(1-\alpha)\gamma_{far}(t)}{\alpha \gamma_{far}(t) + 1} \quad (2)$$

The instantaneous throughput is calculated based on the selected MCS corresponding to the received SINR. Let  $\bar{R}_k(t)$  denote the past average throughput of UE  $k$  at time  $t$ . For an OMA candidate, one UE is allocated to a radio resource, and the PF metric is defined as

$$PF_{OMA}(k, t) = \frac{R_k^{OMA}(t)}{\bar{R}_k(t)} \quad (3)$$

For a NOMA candidate, the PF metric of the NOMA pair consisting of near UE  $n$  and far UE  $f$  is defined as the sum of the PF metrics of the two UEs:

$$PF_{NOMA}(n, f, t) = \frac{R_{near}^{NOMA}(t)}{\bar{R}_{near}(t)} + \frac{R_{far}^{NOMA}(t)}{\bar{R}_{far}(t)} \quad (4)$$

where  $R_{near}^{NOMA}(t)$  and  $R_{far}^{NOMA}(t)$  are the instantaneous throughput of the near UE and far UE when NOMA is applied, respectively. The scheduler searches the predefined Full Search Power Allocation (FSPA) candidates and selects the far UE and power allocation ratio that maximize the NOMA PF metric. If the NOMA PF metric is higher than the OMA PF metric of the selected UE and the NOMA pair satisfies the

BLER condition, NOMA is applied. Otherwise, OMA is used for the selected UE. This PF-based OMA/NOMA selection avoids applying NOMA to unsuitable UE pairs and aims to mitigate the average throughput degradation caused by CRE.

### III. SIMULATION CONDITIONS AND RESULTS

#### A. Simulation conditions

Table I summarizes the main simulation parameters. The HetNet consists of 19 macro-cell sites with three sectors per site and four pico-BSs per macro-sector, giving 1710 UEs in total (30 per macro-sector). The macro-BS and pico-BS operate at 2.0 GHz/10 MHz and 4.5 GHz/100 MHz, respectively, using UMa and UMi path loss models together with Rayleigh fading and log-normal shadowing (8 dB and 10 dB, respectively) [8]. UEs are uniformly and randomly distributed and move at 3 km/h. As an initial evaluation under a fully loaded condition, full-buffer traffic is assumed. PF scheduling and 32-level MCS adaptation (QPSK to 1024-QAM) [9] are also assumed. For imperfect SIC evaluations, the residual interference factor  $\beta$  is varied from 0 to 1.00 in increments of 0.10, as detailed in Section III-G. For each scenario, the throughput of each UE is averaged over 1000 scheduling steps. The average and 5-percentile user throughputs are then calculated over all UEs, and the reported results are averaged over 30 independent random deployment scenarios, in which both pico-BSs and UEs are randomly deployed. The received SINR includes co-channel interference from neighboring BSs within the same tier, namely, neighboring macro-BSs at 2.0 GHz and neighboring pico-BSs at 4.5 GHz.

TABLE I. PRIMARY SIMULATION PARAMETERS

| Parameter                             | Assumption                                                                                                                  |                             |
|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------|-----------------------------|
|                                       | macro-BS                                                                                                                    | pico-BS                     |
| Cell layout                           | Hexagonal grid, 19 cell sites<br>3 sectors                                                                                  | 4 pico-BSs per macro-sector |
| Cell radius                           | 289 m (ISD=500 m)                                                                                                           | -                           |
| Carrier frequency                     | 2.0 GHz                                                                                                                     | 4.5 GHz                     |
| System bandwidth                      | 10 MHz                                                                                                                      | 100 MHz                     |
| Tx power                              | 46 dBm                                                                                                                      | 25 dBm                      |
| Tx height                             | 32 m                                                                                                                        | 10 m                        |
| Tx antenna gain                       | 14 dBi                                                                                                                      | 5 dBi                       |
| Path loss model                       | UMa                                                                                                                         | UMi                         |
| Shadowing                             | 8 dB                                                                                                                        | 10 dB                       |
| Channel model                         | Rayleigh fading                                                                                                             |                             |
| Noise density                         | -174 dBm/Hz                                                                                                                 |                             |
| UE mobility                           | 3 km/h                                                                                                                      |                             |
| UE distribution                       | Uniform random distribution                                                                                                 |                             |
| Link adaptation                       | 32 MCS (QPSK to 1024-QAM)                                                                                                   |                             |
| Scheduling algorithm                  | Proportional fair                                                                                                           |                             |
| Traffic model                         | Full buffer                                                                                                                 |                             |
| Number of UEs                         | 30 UEs per macro-sector, total 1710                                                                                         |                             |
| Scheduling interval                   | 0.5 ms                                                                                                                      |                             |
| Target BLER                           | 10%                                                                                                                         |                             |
| Averaging interval of user throughput | 500 ms (1000 scheduling steps)                                                                                              |                             |
| Maximum number of multiplexed UEs     | 1                                                                                                                           | 2                           |
| SIC assumption                        | Perfect SIC and imperfect SIC                                                                                               |                             |
| Residual interference factor, $\beta$ | 0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, and 1.00                                                           |                             |
| FSPA candidates for near UE $\alpha$  | FSPA-1: 0.22<br>FSPA-5: 0.12, 0.17, 0.22, 0.27, 0.32<br>FSPA-10: 0.12, 0.15, 0.17, 0.19, 0.22, 0.25, 0.27, 0.29, 0.32, 0.35 |                             |

In the proposed scheme, NOMA is applied only to pico-BSs, and up to two UEs can be multiplexed on the same radio resource. Unless otherwise stated, perfect SIC is assumed in Sections III-B–III-F, whereas imperfect SIC is evaluated separately in Section III-G. In the NOMA pairing process, a native pico-cell UE is paired with a CRE UE only when the near UE can decode the far UE signal. The transmission power ratio for NOMA is selected by FSPA, where the scheduler searches for a predefined set of power allocation candidates and selects the candidate with the highest PF metric. In this paper, three FSPA configurations are evaluated: FSPA-1, FSPA-5, and FSPA-10. FSPA-1 uses one fixed power allocation ratio, FSPA-5 uses five candidate power allocation ratios, and FSPA-10 uses ten candidate power allocation ratios [10]. Increasing the number of FSPA candidates linearly increases the number of SINR and MCS evaluations per candidate UE pair, thereby increasing the scheduling complexity.

#### B. Average User Throughput

Fig. 4 shows the average user throughput for different CSO values. The horizontal axis represents the CSO value applied to pico-BSs, and the vertical axis represents the average user throughput. The horizontal reference line indicates the average user throughput without CRE. The average user throughput without CRE is 39.94 Mbps. In the OMA case, the average user throughput decreases as the CSO increases because more UEs are offloaded from macro-BSs to pico-BSs, and the radio resources of pico-BSs are shared among more UEs. In the NOMA cases, perfect successive interference cancellation (SIC) is assumed at the near UEs.

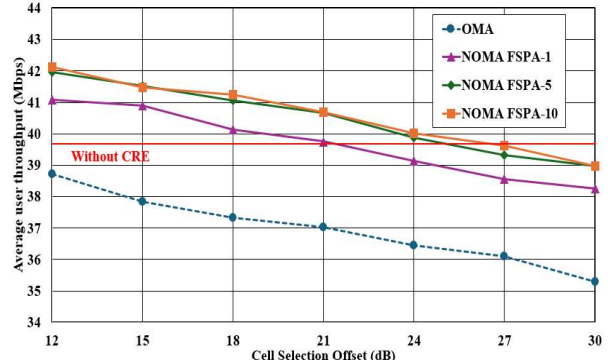


Fig. 4. Average user throughput versus CSOs.

By applying the proposed NOMA scheme, the average user throughput is improved compared with OMA under the same CSO condition. This improvement is obtained because a native pico-cell UE and a CRE UE can be multiplexed on the same radio resource at a pico-BS. Therefore, the proposed scheme can reduce the resource-sharing burden caused by CRE and mitigate the resulting average throughput degradation.

The throughput improvement also depends on the number of power allocation candidates. Compared with FSPA-1, FSPA-5 and FSPA-10 tend to achieve higher average throughput because the scheduler can select a more suitable power allocation ratio according to the channel conditions of the near and far UEs. The gain from FSPA-5 to FSPA-10 is relatively small, but FSPA-10 provides the highest or comparable average throughput in most CSO conditions.

### C. 5-percentile User Throughput

Fig. 5 shows the 5-percentile user throughput for different CSO values. The horizontal axis represents the CSO value applied to pico-BSs, and the vertical axis represents the 5-percentile user throughput. The horizontal reference line indicates the 5-percentile user throughput without CRE. The 5-percentile user throughput without CRE is 1.21 Mbps. As the CSO increases, the 5-percentile user throughput increases because cell-edge UEs are offloaded from macro-BSs to pico-BSs. This result confirms that CRE is effective in improving the 5-percentile user throughput.

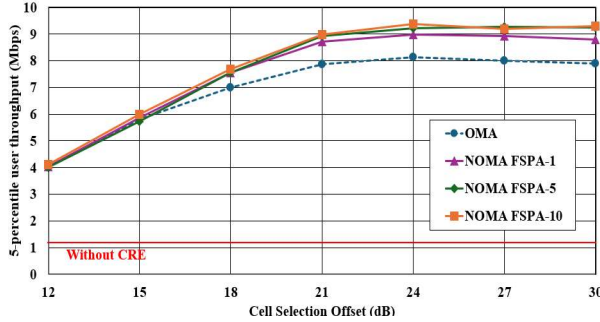


Fig. 5. 5-percentile user throughput versus CSO.

When NOMA is applied, the 5-percentile user throughput is maintained or slightly improved compared with OMA for most CSO values. This indicates that applying NOMA to pico-BSs improves the average user throughput without losing the 5-percentile throughput improvement achieved by CRE. FSPA-5 and FSPA-10 provide higher 5-percentile throughput than FSPA-1 because the power allocation ratio can be selected more flexibly for UE pairs.

### D. Analysis of UE Connection Ratio

Fig. 6 shows the UE connection ratio for different CSO values. As the CSO increases, the ratio of CRE UEs connected to pico-BSs increases, while the ratio of UEs connected to macro-BSs decreases. Since the proposed NOMA pairing is performed between native pico-cell UEs and CRE UEs connected to the same pico-BS, an increase in CRE UEs increases the number of far-UE candidates for NOMA pairing.

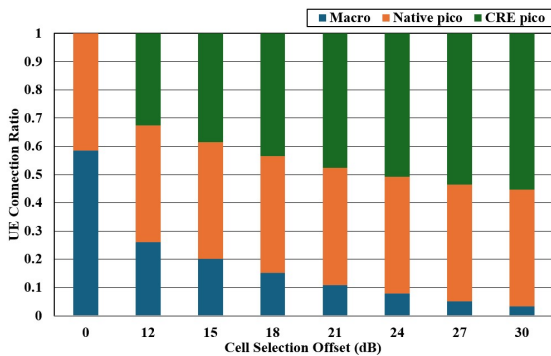


Fig. 6. UE connection ratio for different CSO values.

At CSO = 18 dB, the network-wide proportions of native pico-cell UEs and CRE UEs become approximately balanced. This balance increases the likelihood that both UE types are available at the same pico-BS for NOMA pairing. However, when the CSO exceeds 18 dB, more UEs with relatively poor pico-BS channel conditions are offloaded to pico-BSs. As a result, the SINR of far UEs tends to decrease, leading to the

selection of lower MCS levels. Therefore, although a larger CSO increases the number of CRE UEs, excessive CSO values limit the throughput gain achieved by NOMA.

### E. NOMA Selection Ratio

Fig. 7 shows the NOMA selection ratio for different CSO values and FSPA configurations. The horizontal axis represents the CSO, and the vertical axis represents the NOMA selection ratio, defined as the percentage of radio resources on which NOMA is selected. The selection ratio is calculated by dividing the number of resources where NOMA is applied by the total number of scheduled radio resources. Note that the total number of resources also includes pico-BSs where NOMA cannot be applied because no eligible native pico-cell UE and CRE UE pair exists.

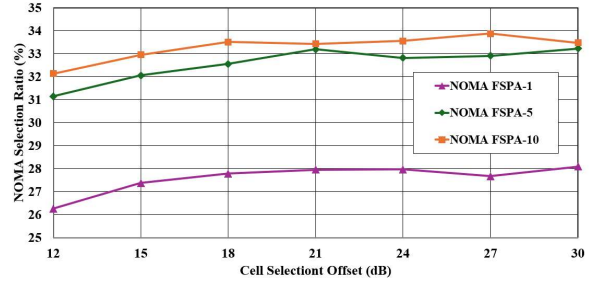


Fig. 7. NOMA Selection Ratio for different CSO values.

The NOMA selection ratio increases as the CSO is increased from 12 dB to 18 dB. However, further increasing the CSO provides only a marginal increase in the NOMA selection ratio, while the channel conditions of the additionally offloaded UEs tend to deteriorate. As a result, although larger CSO values slightly increase the NOMA selection ratio, the degradation in channel quality limits the throughput improvement. Considering Figs. 4–7, CSO = 18 dB provides a favorable trade-off between average and 5-percentile user throughput under the considered conditions.

### F. Average User Throughput Gain over OMA

Fig. 8 shows the average user throughput gain of NOMA with FSPA-10 over OMA under the same CSO condition. The proposed scheme achieves a gain of 3.39–3.91 Mbps over the evaluated CSO range. The maximum gain of 3.91 Mbps is obtained at CSO = 18 dB, which coincides with an approximately balanced distribution of native pico-cell UEs and CRE UEs. For larger CSO values, the gain remains between approximately 3.5 and 3.7 Mbps with minor fluctuations.

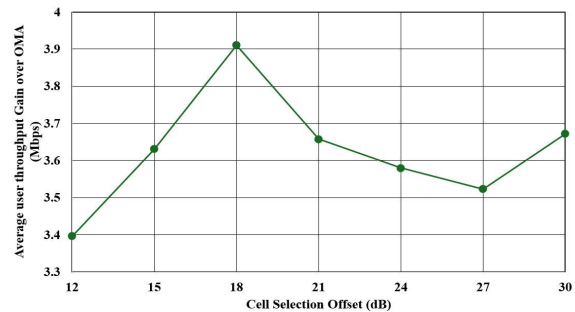


Fig.8. Average user throughput Gain for different CSO values.

### G. Impact of Imperfect SIC

The results in Sections III-B–III-F assume perfect SIC, in which the far-UE signal is perfectly cancelled before the near UE decodes its own signal. In practice, receiver imperfections, channel estimation errors, and error propagation may leave residual interference after SIC [11]. We model this effect using a residual interference factor  $\beta$ , defined as the fraction of the far-UE signal power remaining after cancellation. The near-UE SINR is given by

$$\gamma_{near}^{NOMA}(t) = \frac{\alpha \gamma_{near}(t)}{1 + \beta(1 - \alpha) \gamma_{near}(t)} \quad (5)$$

where  $\beta = 0$  corresponds to perfect SIC. Previous studies have investigated residual interference factors ranging from 0.02 to 0.5, depending on the assumed receiver implementation and evaluation scenario [11]. In this paper, residual interference factors of  $\beta = 0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90$ , and 1.00 are considered to evaluate the sensitivity of the proposed scheme to imperfect SIC. Values above 0.50 are included as stress-test cases to examine the limiting behavior as SIC becomes ineffective. The evaluation is conducted for the representative configuration of CSO = 18 dB with FSPA-10. Under imperfect SIC, the residual-interference-adjusted SINR in (5) is used for MCS selection, PF metric calculation, and throughput calculation. As an additional baseline, we consider the adaptive CRE scheme proposed in [12]. UEs are ranked by their downlink SINR from the macro-BS, and CSO<sub>low</sub> = 9 dB and CSO<sub>high</sub> = 18 dB are applied to the higher- and lower-SINR halves, respectively.

Fig. 9 compares the fixed-CRE OMA baseline, the adaptive CRE baseline, and the proposed NOMA scheme under different residual interference factors. Under perfect SIC ( $\beta = 0$ ), the proposed scheme achieves the highest average and 5-percentile user throughputs, 40.23 Mbps and 7.71 Mbps, respectively. At  $\beta = 0.10$ , these values decrease to 37.69 Mbps and 7.09 Mbps, only 0.21 Mbps and 0.02 Mbps above the fixed-CRE OMA baseline, indicating that the NOMA advantage is nearly lost. For  $\beta \geq 0.20$ , the proposed scheme does not improve both throughput metrics simultaneously compared with the fixed-CRE OMA baseline. These results suggest that the residual interference factor should be below 0.10 to obtain a clear NOMA gain. Although the adaptive CRE baseline provides an average throughput of 38.11 Mbps, its 5-percentile throughput is only 4.02 Mbps. Therefore, when the residual interference is sufficiently small, the proposed scheme provides a favorable balance between average and cell-edge throughput.

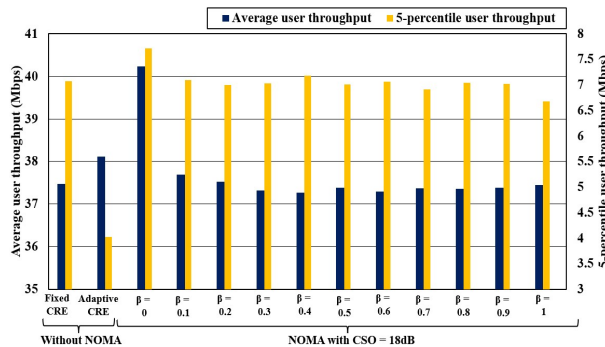


Fig. 9. User throughput under imperfect SIC compared with fixed-CRE and adaptive CRE.

### IV. CONCLUSION

In this paper, we investigated the application of NOMA to pico-BSs in CRE-based HetNets. In the proposed scheme, native pico-cell UEs and CRE UEs are paired for NOMA transmission, and OMA or NOMA is adaptively selected based on PF scheduling metrics. Simulation results showed that the proposed scheme improves the average user throughput over OMA under the same CSO condition while maintaining the 5-percentile throughput improvement achieved by CRE. In particular, FSPA-10 achieved an average throughput gain of 3.39–3.91 Mbps over OMA, with the maximum gain obtained at CSO = 18 dB. The sensitivity to imperfect SIC was evaluated for residual interference factors from  $\beta = 0$  to 1.00. Under perfect SIC, the proposed scheme achieved average and 5-percentile user throughputs of 40.23 Mbps and 7.71 Mbps, respectively. At  $\beta = 0.10$ , these values decreased to 37.69 Mbps and 7.09 Mbps and became nearly identical to the fixed-CRE OMA baseline. For  $\beta \geq 0.20$ , no simultaneous improvement in both metrics was observed. These results suggest that a clear NOMA gain can be obtained only when the residual interference factor is below 0.10, highlighting the need for sufficiently accurate SIC.

As future work, we plan to optimize the power allocation ratio in FSPA-1 to reduce the computational complexity of the scheduling process.

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