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Throughput-Based Satisfaction Maximization for a Multi-Cell Downlink OFDMA System Considering Imperfect CSI

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Abstract— **In realistic scenarios, imperfect Channel State Information (CSI) at the transmitter can induce the resource assignment to a user whose real channel state cannot support a required data rate, harming the system performance. This work focuses on the impacts of the CSI imperfections as well as of the interference in multicellular scenarios on the performance of the Throughput-Based Satisfaction Maximization (TSM) Radio Resource Allocation (RRA) algorithm. Simulation results indicate that, in this scenario, the TSM algorithm achieves higher satisfaction percentages than the Signal-to-Interference plus Noise (SINR) Maximization algorithm, in spite of its higher sensitivity to both effects.**

Keywords— **RRA, TSM, imperfect CSI, inter-cell interference**

I. INTRODUCTION

In a competitive environment characterized by increasing market demands, cellular network operators must adopt new technologies to enhance the performance of the wireless communication systems managed by them. To ensure the provision of better radio services and better return on investment, efficient Radio Resource Allocation (RRA) strategies are essential to improve coverage, capacity and Quality of Service (QoS). These techniques increase the number of satisfied clients. In this work, we investigate the problem of user satisfaction maximization using a utility-based resource allocation algorithm.

This study aims at developing a fair resource assignment strategy. This technique ought to ensure that users achieve their QoS requirements, regardless their channel conditions. Other papers in the literature have already addressed the issue of resource allocation assuming perfect Channel State Information (CSI) at the transmitter [1], [2]. However, the perfect CSI assumption (without estimation errors nor channel feedback delay) can significantly deteriorate the system performance [3], [4]. Unsuccessful transmissions can occur when the BS assigns a certain rate to a user based on a nominal CSI that cannot be supported by the true channel state [5].

It was demonstrated in [6] that the introduction of a noise term in the CSI estimation yields significant performance degradation. The statistical description of the CSI uncertainty can be exploited aiming at maximizing the system capacity, as illustrated in [5]. Besides the throughput metric, fairness can also be considered on resource allocation schemes considering imperfect CSI, which has already been investigated in [7].

We investigate the downlink of cellular networks based on Orthogonal Frequency Division Multiple Access (OFDMA). Although different Non-Real Time (NRT) traffic models, such as World Wide Web (WWW) and File Transfer Protocol (FTP), could be contemplated, we employ full buffer models to simulate the worst case scenario in which all users are greedy for resources.

Another source of performance degradation is the interference of the multi-cellular scenario considered. Therefore, it is an issue of relevant concern for the development of new communication systems [8].

In [9], a new RRA algorithm was proposed, called Throughput-based Satisfaction Maximization (TSM). This technique uses a sigmoidal utility function based on the users' throughput in order to improve user satisfaction in a scenario with NRT services. The results already available assume perfect CSI in a single-cell. The present work evaluates the TSM technique in a more realistic scenario. We study the impacts of multi-cell interference as well as CSI imperfections (delay of the channel measurements).

In a multi-cellular scenario there are different RRA coordination schemes. This work considers an autonomous distributed scheme, i.e., there is no central entity for coordination, and channel scheduling is done by each cell based on the local CSI [8]. The autonomous RRA simplifies the network management, eliminating the signaling overhead between cells and allowing fast real-time processing. Besides that, it permits a more efficient adaptation to channel and traffic conditions [10].

The paper is organized as follows. In Section II, a general description of our system model is given. Sections III and IV describe the formulation of the RRA scheme and the simulation results are analyzed, respectively. Finally, the conclusions and perspectives are presented in Section V.

II. SYSTEM MODELING

We consider a downlink multi-cellular OFDMA environment with a set of B Evolved Node Bs (eNBs), sharing the same set $\mathcal{K}$ of K Resource Blocks (RBs). Each eNB b attends a different subset $\mathcal{U}_b$ of U_b User Equipments (UEs). The set of all UEs, $\mathcal{U}$, has size $U = U_b B$. Each eNB manages the resource allocation to the UEs connected to it. We also assume that each UE and eNB is equipped with a single antenna and the total power of each eNB is equal to P_t and is equally distributed among all RBs. Thus, the power $p_{b,k}$ allocated to RB k by eNB b is $p_{b,k} = P_t/K$.

We approximate the channel coefficient $h_{u,b,k}[n]$ between UE u and eNB b in RB k and in Transmission Time Interval (TTI) n by the coefficient of the first symbol of the mid sub-

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carrier that composes the RB. Moreover, we assume that it remains constant during the period of one TTI.

In order to perform the RRA and to calculate the receive and transmit filters, each eNB must have some knowledge about the channel and the Signal to Interference-plus-Noise Ratio (SINR) of its UEs for each RB. The instantaneous SINR $\gamma_{u,k}[n]$ of UE u in RB k in TTI n is given by

$$\gamma_{u,k}[n] = \frac{p_{b,k} d_{u,k}[n] h_{u,b,k}[n] g_{b,k}[n]}{\underbrace{\sum_{j=1, j\neq b}^{B} p_{j,k} d_{u,k}[n] h_{u,j,k}[n] g_{j,k}[n]}_{\text{Interference Power}} + \sigma^2}, \quad (1)$$

where $d_{u,k}[n]$ and $g_{b,k}[n]$ represent the decoder of UE u and the precoder of eNB b in the RB k, respectively, and σ^2 denotes the thermal noise power.

In practice, the channel is estimated by the UE using pilot symbols transmitted by the eNB. The estimated channel can be modeled as described in [11]:

$$\hat{h}_{u,b,k}[n] = \sqrt{\psi} h_{u,b,k}[n] + \sqrt{(1-\psi)} \eta[n], \quad (2)$$

where $\psi \in (0,1)$ denotes the quality of the channel estimation and $\eta[n] \in \mathbb{C}$ represents a channel estimation error, which is modeled as a Zero Mean Circularly Symmetric Complex Gaussian (ZMCSCG) random variable, with $\mathbb{E}\{|\eta[n]|^2\} = \mathbb{E}\{|h_{u,b,k}[n]|^2\}$. Moreover, the UEs report periodically their channel estimations to their eNB by a feedback link, offering an outdated CSI to the RRA algorithm.

For simplicity, we assume that all UEs report in periods of δ TTIs and the eNB receives the measure delayed of Δn TTIs. Thus, the CSI used by the eNB is given by

$$\tilde{h}_{u,b,k}[n] = \hat{h}_{u,b,k}[n - \Delta n - (n \mod \delta)]. \quad (3)$$

In this work, we are interested at studying the CSI imperfections regarding the delay of the measurements. Hence, we consider that the channels can be perfectly estimated ($\psi = 1$) and that the reports are performed at every TTI ($\delta = 1$).

In addition, the eNB must have knowledge about the interference power in order to estimate the UEs' SINR. It is prohibitive to obtain information about all interference links, thus we consider that the UEs can estimate the instantaneous total interference power, and filter these results along W TTIs. Interference is estimated regardless of the RBs and is smoothed using an exponential moving average post-filter estimator [12], which has low complexity. Thus, the estimation of the interference power reported by each UE u to its eNB can be written as

$$\tilde{I}_u[n] = \left(1 - \frac{1}{W}\right) \tilde{I}_u[n-1] + \frac{1}{W} I_u[n], \quad (4)$$

where $I_u[n]$ represents the instantaneous interference estimation and $\tilde{I}_u[n-1]$ denotes the previous filtered interference. We also assume that this value is reported to the eNB together with the channel estimation.

In our scenario, we assume that all decoders are unitary, $d_{u,k}[n] = 1$. On the other hand, we consider the precoders to be equal to the channel matched filter of the scheduled UE u in RB k, i.e., $g_{b,k}[n] = \tilde{h}^*_{u,b,k}[n]$, where $(\cdot)^*$ denotes the conjugate operator. Therefore, the SINR information available in the eNBs is

$$\tilde{\gamma}_{u,k}[n] = \frac{p_{b,k} \left|\tilde{h}_{u,b,k}[n]\right|^2}{\tilde{I}_u[n] + \sigma^2}. \quad (5)$$

In our framework, we assume that the data transmission considers a link adaptation scheme that allows the eNB to transmit with different data rates depending on the estimated SINR $\tilde{\gamma}_{u,k}[n]$ of the scheduled UE u at RB k. So, the data rate allocated by the eNB to UE u in RB k is $r_{u,k}[n] = f(\tilde{\gamma}_{u,k}[n])$, where $f(\cdot)$ represents the link adaptation function. The total UE data transmitted in TTI n is given by $R_u[n] = \sum_{k \in \mathcal{K}_{u,n}} r_{u,k}[n]$, where $\mathcal{K}_{u,n}$ denotes the subset of RBs allocated to the UE u at TTI n.

However, the transmission can fail due to bad channel conditions, wherein the whole information block is lost. Thus, we define $\varphi[n] = \varphi(r_{u,k}[n], \gamma_{u,k}[n])$ as a binary variable equal to 1 if the transmission fails, and 0, otherwise.

Considering a snapshot of N TTIs, the system BLock Error Rate (BLER) is defined as

$$P_e = \frac{1}{NKB} \sum_{n=1}^{N} \sum_{u \in \mathcal{U}} \sum_{k \in \mathcal{K}_{u,n}} \varphi[n] \quad (6)$$

In order to emulate the impact of different interference levels, we use an activity factor α, which means that only $\alpha\%$ of the eNBs are active in average.

With respect to the RRA algorithm, we will assume that all eNBs schedule their resources to their UEs using the TSM algorithm [9], which is described in details in Section III.

III. UTILITY-BASED SCHEDULING FOR IMPROVING SATISFACTION OF NRT SERVICES

Regarding NRT services, the optimization problem considered in this work is the utility maximization in eNB b with respect to the throughput of the UEs, as stated below:

$$\max_{\rho_{u,k}} \sum\nolimits_{u \in \mathcal{U}_b} \Psi\left(T_u[n]\right) \quad (7a)$$

$$\text{subject to} \quad \rho_{u,k} \in \{0,1\},\ \forall u \in \mathcal{U}_b \text{ and } \forall k \in \mathcal{K}, \quad (7b)$$

$$\sum\nolimits_{u \in \mathcal{U}_b} \rho_{u,k} = 1,\ \forall k \in \mathcal{K}, \quad (7c)$$

where $\rho_{u,k}$ is an assignment variable that assumes the value 1 if the RB k is assigned to the UE u and 0 otherwise, and $\Psi\left(T_u[n]\right)$ is a concave and increasing utility function based on the current throughput $T_u[n]$ (average data rate) of the UE u in TTI n. Constraints (7b) and (7c) state that the subsets of resources assigned to different UEs must be disjoint, i.e., the same resource cannot be shared by two or more UEs at the same TTI. Furthermore, the union of all subsets of resources scheduled to different UEs must be limited to the total set of resources available in the system.

Different strategies of resource allocation can be developed according to the type of the chosen utility function. In this work, we analyze the behavior of the TSM algorithm [9]. The eNB chooses the UE $u^\star$ to transmit on RB k in TTI n, if it satisfies the condition given by

$$u^\star = \arg\max_{u \in \mathcal{U}_b} \left\{ r_{u,k}[n] \cdot w_u \right\}, \quad (8)$$

where $r_{u,k}[n]$ denotes the instantaneous achievable transmission rate of UE u with respect to RB k at TTI n, and w_u is a utility-based weight of UE u. If more than one user has the same priority for RB k, a tiebreaker process selects the UE with highest SINR. Not only is the TSM scheduler opportunistic, since it considers the wireless channel quality, but it also provides a QoS-based resource allocation, since it considers the utility-based weights of the UEs.

It is possible to provide high user satisfaction for NRT services with low complexity if we consider a step-like utility function in the resource allocation, e.g. the sigmoidal function, [9]. The TSM policy employs an increasing sigmoidal utility function based on UEs' throughput, according to:

$$\Psi\left(T_u[n]\right) = \left(1 + e^{-\sigma\left(T_u[n] - T_{\text{req}}\right)}\right)^{-1}, \tag{9}$$

where σ is a non-negative parameter that determines the shape of the sigmoidal function, and T_{req} is the throughput requirement for all UEs. Observe that this is an increasing utility function, which means that the higher the throughput, the higher the UEs' utility derived from the network. The step-like utility function was chosen in accordance with the definition of satisfaction for NRT services largely employed in the literature. It implies that a given UE becomes satisfied quickly if the throughput approaches and exceeds the requirement. The opposite occurs when the UE throughput decreases to values lower than the requirement.

IV. PERFORMANCE EVALUATION

In this section, we analyze the performance of the TSM scheduler in a scenario with inter-cell interference and imperfect CSI, and compare these results with those obtained when a Max-SINR algorithm was considered. The simulations consider a three-sectored hexagonal cell surrounded by one ring of interfering cells, corresponding to 21 sectors. In order to guarantee the same level of interference in all cells, we implemented the wrap-around technique presented in [13].

We consider that the eNBs provide NRT services to the UEs, where an NRT UE is satisfied if its session throughput is higher or equal to a certain requirement ($T_u[n] \geq T_{\text{req}}$). The satisfaction index is given by the ratio between the number of satisfied UEs and the total number of UEs in the system. The general simulation parameters are presented in Table I.

A. *Interference Analysis*

We consider an NRT full buffer traffic model with an activity factor α (i.e., only $\alpha\%$ of the eNBs are active in average) to evaluate the impact of the interference in the system performance. A perfect CSI is considered. The selection of which eNBs are actives in each TTI is performed randomly.

Figure 1 presents the satisfaction index as a function of the number of UEs per cell. TSM and Max-SINR algorithms with different activity factors are evaluated. It can be seen that the satisfaction index of both algorithms decreases when the load increases, as expected. This happens due to the limited number of RBs available in the eNB, which becomes increasingly scarce with a higher number of UEs.

TABLE I: Simulation parameters

Parameter	Value
Number of cells	21
Maximum eNB transmit power	43 dBm
BS antenna radiation pattern	Three-sectored
Cell radius	1 km
UE speed	3 km/h
Carrier frequency	2 GHz
System bandwidth	5 MHz
Sub-carrier bandwidth	15 kHz
Number of RBs	25
Path loss	$128.1 + 37.6 \log_{10} d$ [a]
Channel Coherence Band	90 ms
Antenna Gain [14]	$G_h(\theta_h) + G_v(\theta_v)$ [b]
Downtilt Angle	8 degrees
Log-normal shadowing st. dev.	8 dB
Small-scale fading [15]	3GPP Typical Urban
AWGN power per sub-carrier	-123.24 dBm
Noise figure	9 dB
Link adaptation	Link level curves from [16]
Transmission Time Interval	1 ms
NRT traffic model	Full buffer w/ activity factor
User throughput requirement	512 kbps
Parameter σ	6.157×10^{-6}
Multi-antenna configuration	SISO
Window of the exponential filter	10 TTIs
Simulation time span	15 s
Number of simulation runs	30

[a] d is the distance to the eNB in km.

[b] θ_h and θ_v are the horizontal and vertical angles related to the eNB.

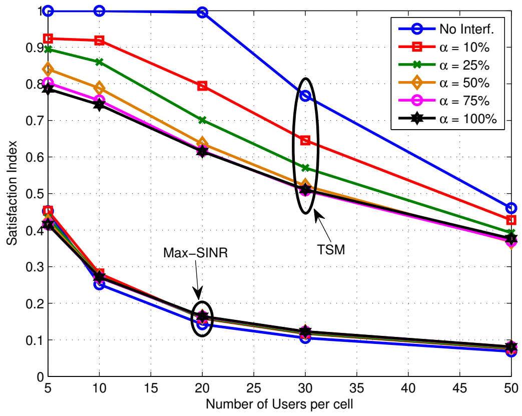


Fig. 1: Satisfaction index for different interference levels.

The activity factor has no significant impact over the UE satisfaction for the Max-SINR scheduler, since the UEs with the best SINRs are always attended and get satisfied, while the remaining UEs might starve. Differently, the TSM presents a satisfaction degradation when the activity factor increases. The TSM considers the QoS of the UEs besides their instantaneous rates, thus being less opportunistic than the Max-SINR. It often schedules UEs with low SINR, which are affected by the interference and have lower throughput. The high variance of the interference compromises the accuracy of interference estimates used to compute SINR values and map them to data rate values using the link level curves. Since the TSM is sensitive to variations in the utility value around the rate requirement, it is more affected by such innacuracies, which lead to higher BLER and higher variation of the UEs' throughputs.

For higher loads, the impact of the activity factor is mitigated.The resource sharing starts to dominate, since the eNB has to attend a larger number of UEs with a limited amount of RBs. It is worth to mention that the TSM presents higher satisfaction than the Max-SINR in spite of being more sensitive to the interference variations.

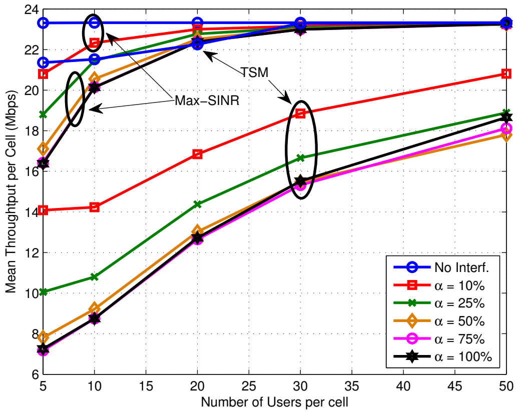


Fig. 2: Mean throughput per cell for different interference levels.

The mean throughput per cell is depicted in Fig. 2. Concerning the Max-SINR scheduler, the impact of the interference is more evident when the number of attended UEs in the eNB is small, due to low multiuser diversity. However, the eNB throughput tends to its maximum capacity when we have more attended UEs. Regarding the TSM algorithm, the throughput per cell increases when the interference power decreases. However, notice that the cell throughput remains almost the same for $\alpha \geq 50\%$, regardless the interference power. This indicates that TSM provides a capacity floor, even in scenarios with high interference.

Considering the TSM scheduler, even for low interference power ($\alpha = 10\%$), the throughput is highly degraded compared with the case without interference. It happens because the UEs are not able to transmit with high Modulation and Coding Scheme (MCS) when the interference increases.

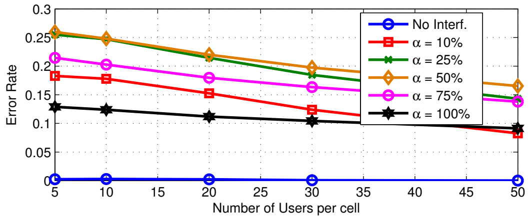
In Fig. 3, we notice that the BLER is very low in a scenario without interference. On the other hand, the BLER achieves its maximum value when $\alpha = 50\%$ for both schedulers. This behavior is a consequence of the lack of stability in the interference estimation in the RRA algorithm, incurring in a bad resource allocation. For $\alpha \geq 50\%$, the interference estimation becomes more reliable, which allows a better scheduling decision.

Concerning the BLER, the Max-SINR leads to fewer errors than the TSM, mainly due to the fact that the UEs with better channel gains always get the resources.

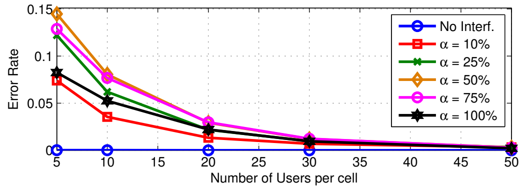
B. CSI Analysis

In the analysis of the CSI imperfections, the UEs are able to estimate their channels perfectly, but the eNB receives their measurements delayed by Δn TTIs. We employ a full buffer traffic model with $\alpha = 100\%$ (full interference).

Figure 4 presents the satisfaction index as a function of the number of UEs attended per cell, considering TSM and Max-SINR algorithms with different measurement delays in the CSI. It can be noticed that the satisfaction index obtained with the TSM scheduler is more sensitive to the CSI imperfections than the obtained with the Max-SINR.



(a) TSM Algorithm



(b) Max-SINR Algorithm

Fig. 3: BLER for different interference levels.

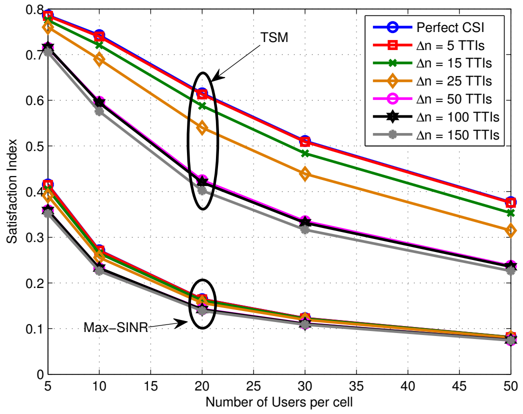


Fig. 4: Satisfaction index considering imperfect CSI.

The increasing CSI delay has no considerable effects on the satisfaction index obtained by the Max-SINR algorithm, even when the delay is higher than the channel coherence time, i.e., a scenario with low correlation between the CSI and the actual channel. The Max-SINR tends to select UEs that are close to the eNB, so that the SINR is dominated by the large-scale fading. This fact makes the Max-SINR technique less sensitive to CSI measurement delays.

Since the TSM algorithm schedules UEs considering their QoS parameter, the scheduler can incur in an improper scheduling decision due to the CSI delay, and so allocate resources that will be certainly wasted.

The mean cell throughput is depicted in Fig. 5. Looking at Fig. 2, one can notice that the Max-SINR scheduler is more harmed by the imperfections on the CSI than the interference power. For higher delays, the total system capacity is not reached, even for a high number of UEs. When the delay increases the CSI becomes less correlated to the real channel information. This leads to incorrect precoding, incurring in a higher BLER, as shown in Fig. 6.

In the TSM scheduler, when the number of UEs increases, the difference between the mean eNB throughput also increases, as a consequence of the high number of UEs that the algorithm tries to satisfy with its limited number of resources. Furthermore, the eNB is more likely to incur in errors when transmitting to UEs more distant from it, as shown in Fig. 6.

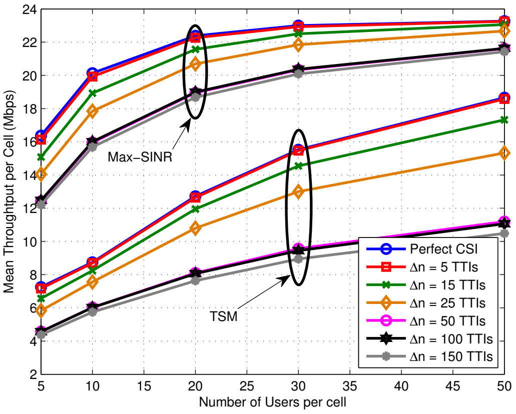
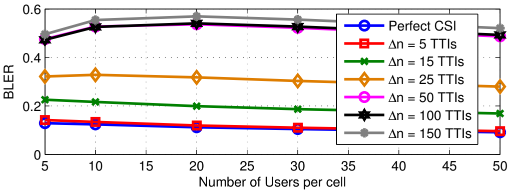
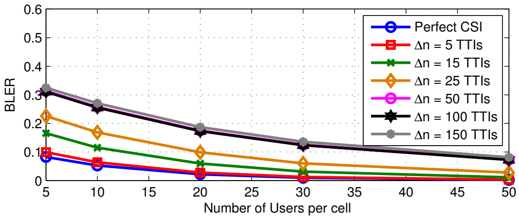


Fig. 5: Mean throughput per cell considering imperfect CSI.



(a) TSM Algorithm



(b) Max-SINR Algorithm

Fig. 6: BLER with imperfect CSI.

It is important to note that the impact of imperfect CSI on both algorithms can be neglected for small measurement delays, such as $\Delta n = 5$ TTIs. However, if the delay is greater than half the channel coherence time, the CSI and the real channel become almost uncorrelated. This fact decreases the satisfaction index and the eNB throughput drastically by increasing the BLER to unacceptable values.

V. CONCLUSION

In this paper, we investigate the impacts of the CSI imperfections and multi-cell interference on the performance of the Throughput-based Satisfaction Maximization (TSM) algorithm. The Max-SINR algorithm was used as a reference.

Concerning the interference analysis, the TSM presents a better satisfaction in spite of being more sensitive to the interference variations. Regarding the Max-SINR scheduler, the UEs with the best SINRs are always attended and get satisfied, while the remaining UEs might starve. Differently, the TSM considers the QoS of the UEs besides their instantaneous rates. It often schedules UEs with low SINR, which are affected by the interference and have reduced throughput.

Even presenting a larger sensitivity to CSI imperfections, the TSM also achieves higher UE satisfaction percentages than the Max-SINR scheduler. On one hand, the Max-SINR tends to select UEs that are close to the eNB, so that the SINR is dominated by the large-scale fading. Therefore, it becomes less sensitive to CSI delays. On the other hand, since the TSM algorithm schedules UEs considering a QoS-based utility function, it is more likely to incur in improper scheduling decisions due to delayed CSI measurements.

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