Flexible Spectrum Sharing and Interference Coordination for Low Power Nodes in Heterogeneous Networks

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***Abstract*—Heterogeneous Networks (HetNet) have been proposed as a means of boosting the coverage in areas where users experience weak wireless connectivity. In HetNets, due to the massive deployment of Low Power Nodes (LPN) along side the usual Macro Base Stations (MBS), inter-cell interference becomes a significant issue which, if not properly handled, may degrade the network throughput and the macro-cell edge users performance.**

In this paper, we focus on the problem of the inter-cell interference to the Macro User Equipments (MUE) generated by the LPNs. We propose an algorithm for flexible spectrum usage among LPNs that enhances macro cell-edge user throughput. By means of a dynamic redistribution of the frequency resources among MBSs and LPNs, this algorithm reduces the harmful interference generated by the LPNs to the macro cell-edge users, hence increasing the throughput of the latter. In addition to helping the terminals which experience high interference, the proposed solution also limits the overall reduction in network throughput, which is usually one of the side effects of interference coordination in HetNets.

The simulation results show that, compared to a full frequency reuse for the LPNs, the proposed algorithm improves the throughput of the macro cell-edge users, which are usually the ones experiencing the lowest performance within the network. Overall, with limited impact in terms of HetNet throughput reduction and with good benefit to the cell-edge users performance, this algorithm represents an effective solution to the inter-cell interference problem affecting the HetNets.

***Index Terms*—Heterogeneous networks, spectrum sharing, interference coordination, pico-cells, low power nodes, Flexible Spectrum Usage (FSU), Long Term Evolution (LTE).**

I. Introduction

In order to enhance the coverage in those areas where users may experience bad wireless connectivity from Macro Base Stations, network operators have recently started deploying Low Power Nodes [1]. Such a network in which MBSs and LPNs using the same Radio Access Technology coexist in order to improve the wireless coverage is referred to as a HetNet [2].

However, due to the proximity of several Base Stations (BS) sharing the same spectrum, users may experience high inter-cell interference which can degrade the network performance [2], [3]. In this paper we deal with the problem of the high inter-cell interference in the downlink of HetNets and we focus specifically on the macro-users. Indeed, in HetNet scenarios, the MUEs located at the macro-cell edges are typically victims of this interference, as these UEs are located far from the serving MBS and in proximity of the interfering LPNs.

In order to combat the inter-cell interference, frequency planning based techniques (e.g. Hard Frequency Reuse or Soft Frequency Reuse [2]) for Inter-Cell Interference Coordination (ICIC) are usually adopted in macro-cells networks. However, due to the large number of lower power nodes deployed in HetNets, the frequency planning of massive LPN deployments is excessively complex [2]. Hence, ICIC for LPN in HetNet requires a more flexible approach for resource sharing compared to the fixed frequency reuse schemes.

In recent years, some solutions for ICIC in HetNets have been proposed. In [4], the authors propose a Q-learning based approach where each Femto Base Station (FBS) tries to learn a spectrum allocation pattern that maximizes the femto-cell throughput and, at the same time, does not interfere with the neighboring MUEs. In [5], the femto to macro inter-cell interference coordination is achieved by a planned orthogonal subcarrier assignment between MBSs and LPNs. This approach, while being beneficial in terms of cell-edge user throughput does however considerably limit the network spectral efficiency. In most of the existing solutions, the ICIC task for the HetNet is limited to the reduction of transmission power or to the reuse of common bands by adjacent BSs. Unfortunately, any restriction to the BSs' power/band resources brings with it a cost in terms of network throughput reduction.

In this paper we further develop the concept of ICIC in HetNets and provide a novel approach for boosting the performance of the MUEs suffering for high LPN interference. In addition to improving the performance of the cell-edge users, we also strive to contain the network throughput reduction when carrying out ICIC for the HetNet. We propose a distributed Flexible Spectrum Usage Algorithm for HetNets (FSUAH) which makes use of a joint ICIC/user scheduling technique. FSUAH attempts to provide a target throughput at the cell-edge UEs first by acting on the MBS user scheduler, which is assumed to be of a Proportional Fair (PF) kind. Then secondly and only when it is not possible to achieve our target through the scheduler alone, the inter-cell interference is limited by dynamically reducing the spectrum resources assigned to the adjacent LPNs. Overall, we show that it is possible to enhance the HetNet performance by jointly using

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a PF user scheduler, carried out in an uncoordinated manner among the MBSs, and a flexible spectrum sharing technique for ICIC purposes.

The paper is organized as follows. In Section II we propose the FSUAH algorithm, while in Section III the simulation results are presented and discussed. The conclusions are drawn in Section IV.

II. Algorithm: FSUAH

A. System overview and algorithm framework

The FSUAH has been designed for Orthogonal Frequency Division Multiple Access (OFDMA) based systems. Even though in this paper we do not consider any specific mobile wireless communication standard, we will refer to Long Term Evolution (LTE) for some of the physical layer implementation details, such as the frequency-time resources organization. For example, in LTE, the smallest frequency and time resource unit we can make use of is the Resource Block (RB) [6].

Although FSUAH is a distributed algorithm which runs in each MBS and in each LPN, this algorithm only controls the spectrum in use by the LPNs. As the frequency planning in a macro cell layer scenario is feasible and of common practice for ICIC purposes [2], we assume the MBSs use a hard frequency reuse scheme (i.e. reuse 3). Fig. 1 shows an example of a possible scenario, with 3 MBSs coexisting with 3 LPNs. Each MBS sends feedback to the surrounding LPNs in order to signal them whenever MUEs experience high interference. As proposed in [7], this feedback could be represented by the High Interference Indicator (HII) which reports the indices of the highly interfered RBs to the LPNs. The effect of this feedback is to reduce the frequency resources in use by the adjacent LPNs. The usage of HIIs is the only kind of cooperation of which the FSUAH makes use. No cooperation is required between MBSs or between LPNs. Overall, MBSs and LPNs share the same common frequency resource pool.

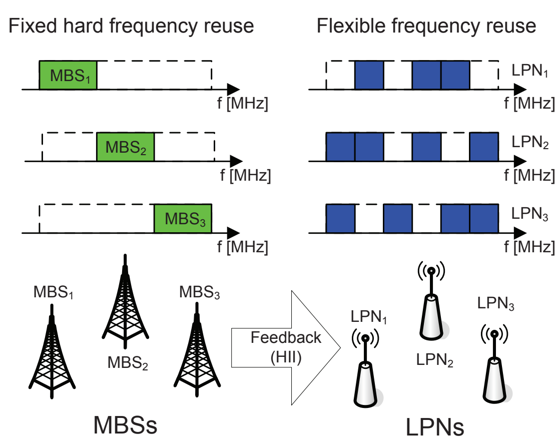


Fig. 1: MBS and LPN spectrum reuse.

B. User operating points

In this section we introduce the concept of *operating points* which will be used as a tool for triggering the algorithm state transitions. We define a *user operating point* as a couple of metrics (i.e. *cell-edge user throughput* or R_{ce} and *average user throughput* or R_{av}) which will be represented in a 2D-plot. The operating points are a graphical representation of the throughput experienced by the cell UEs and the resource sharing fairness among the UEs themselves. We define the *fairness degree* as the ratio R_{ce}/R_{av}; the higher the fairness, the closer to 1 R_{ce}/R_{av} will be.

In this paper, we assume that UEs are assigned RBs by means of a Proportional Fair (PF) algorithm which allocates resources to the UEs based on the metric $M = \frac{d^{\alpha}}{r^{\beta}}$, where d is the current throughput experienced by the UE on a given RB and r is a time averaged measure of the throughput experienced by the UE in the past. The parameters α and β allow the fairness of the algorithm to be specified. By keeping α constant and increasing β we increase the PF fairness, while we favor a less fair throughput increase the other way around. The UE with the highest value of M will then be allocated over a given RB.

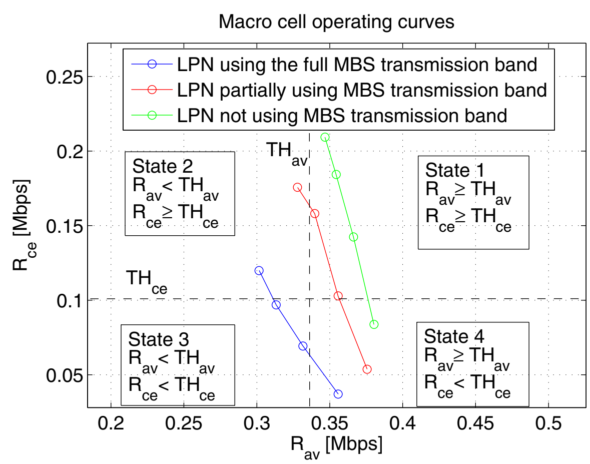


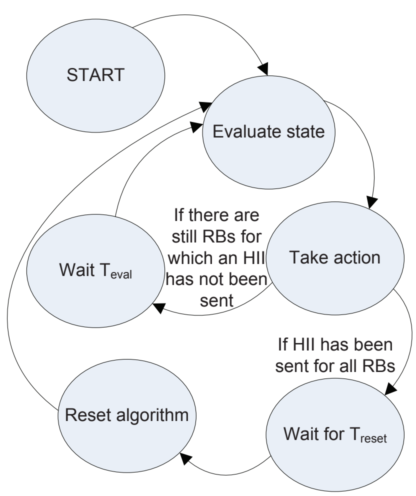
Fig. 2: MBS operating curves and states. Three different operating curves (blue, red, green) are shown, each of them with 4 operating points. Each operating point corresponds to a given set of PF parameters.

As we can see from the example shown in Fig. 2, by means of varying the cell resource share among the same macro cell users (i.e. by varying the PF parameters α and β) we obtain operating points with different fairness degrees; the lines joining these points are the *operating curves*. Assuming that: 1) the portion of band used by the LPNs that overlaps with the band used by the MBS remains constant over time; 2) a PF scheduler is used for UEs scheduling; an operating curve is obtained by varying the fairness degree of the PF scheduler. Hence, each operating curve is obtained by keeping the LPN interference conditions constant (i.e. the LPNs transmit over a given portion of band) and by varying the PF scheduler fairness degree or, equivalently, by varying the PF parameters. If we vary the LPNs interference conditions we then obtain a different operating curve.

C. Algorithm running in the MBS

The aim of the MBS is to attempt to meet two user throughput requirements, which are represented by the performance metric thresholds TH_{ce} and TH_{av} for R_{ce} and R_{av} respectively (refer to Section II-E for further details concerning the TH_{ce} and TH_{av} values setting). In order to achieve this goal, the MBS estimates the operating point (R_{ce}, R_{av}) and compares each of these metrics with their respective thresholds TH_{ce} and TH_{av}. As shown in Fig. 2, the results of this comparison provide the state of the MBS.

The FSU algorithm running in the MBS always tries to achieve the required performance first by adjusting its own PF scheduler parameters rather than requiring a LPN spectrum reduction. In Fig. 2, varying the PF parameters corresponds to moving the MBS towards different operating points along the same operating curve. Only if the MBS is not able to reach the expected throughput requirements by means of adjusting the PF parameters, a HII is issued to attempt to limit the interference from the neighboring LPNs. If any of the LPNs receiving the HII is the actual cause of the interference, the HII has the effect of moving the MBS towards different operating curves (see Fig. 2). The algorithm flow-chart is shown in Fig. 3.



State	Action
1	No action
2	Decrease PF fairness
3	Send HII
4	Increase PF fairness

Fig. 3: Flow-chart of FSU algorithm running in the MBS.

After initialization, the algorithm periodically evaluates the state in the MBS. Based on this state, an action is taken (see table in Fig. 3), after which the algorithm waits for a certain time T_{eval}. This time is necessary to observe the effect of the action on the operating point. If at time t the MBS state is 2 (or 4), the corresponding action (see table in Fig. 3) will bring the MBS state at time $t+1$ into the operating point with lower (or higher) degree of fairness along the same operating curve (see Fig. 2). On the other hand, if at time t the MBS state is 3, a HII will be issued (see table in Fig. 3) in order to attempt a reduction of the interference generated by the LPNs. Assuming that the LPNs receiving the HII are the actual cause of the interference on the MUEs, this HII will bring the MBS state at time $t+1$ into the next right-top operating curve (see Fig. 2). Overall, FSUAH will always try to bring and keep the MBS in one of the operating points in state 1, which is the state where the performance targets are met.

The MBS always keeps track of the RBs for which a HII is sent. If the HIIs are sent for all the RBs in use by the MBS, the MBS waits for a given time T_{reset} before beginning again to respond and take action. In fact, when the HIIs are sent for all the RBs, there is no other way to reduce the interference of the LPNs on the MUEs and hence to bring the MBS to state 1. In this case, after a waiting period T_{reset} has elapsed, some changes within the network may have occurred (i.e. traffic load, users distribution and number of UEs connected to the BSs) and thus it makes sense to reset the algorithm and restart to evaluate the MBS state.

D. Algorithm running in the LPN

As we can see from the flow-chart in Fig. 4, after the initialization, the algorithm works with two parallel flows. One of these is in charge of increasing the number of the RBs used and it is a cyclic operation which runs with period T_{NEW}. The second flow is responsible for limiting the number of RBs usable by the LPN and is driven by the HIIs sent by the MBSs.

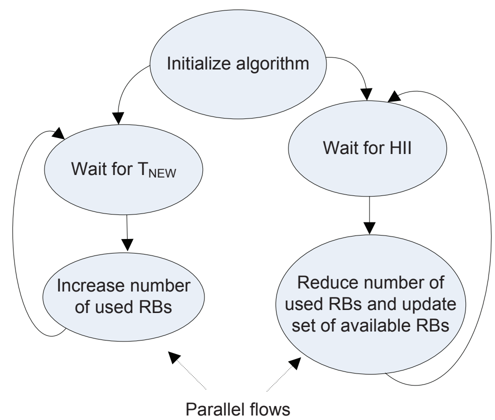


Fig. 4: Flow-chart of FSU algorithm running in the LPN.

Whenever the MBSs issue a HII requiring the LPN to release some given RBs (each HII reports the indices of K RBs), the LPN considers these RBs as non-available for some given time. This means that, when the FSU algorithm has to increase the spectrum in use in the LPN, only the available RBs can be chosen. The LPN will select the L RBs where the UEs experience the highest average SINR.

Each time the LPN receives a HII from the MBSs indicating that some RBs must be released, the LPN will set these RBs as non-available and will stop using them for a period T_L. After a specific time has elapsed, the LPN will set these RBs as available again.

E. Algorithm parameters

Two parameters must be set for the FSUAH running in the MBSs, i.e., the performance targets TH_{ce} and TH_{av}.

These parameters represent the throughput values which are considered to be satisfactory for the MUEs. In fact, setting TH_{ce} and TH_{av} to higher values will trigger FSUAH to attempt the achievement of higher cell-edge and average user throughputs for the MBSs. For this reason, TH_{ce} and TH_{av} will drive the performance achievable by the algorithm.

Since solving a maximization problem for ensuring an optimal setting of the parameters TH_{ce} and TH_{av} is beyond the scope of this paper, we follow a different approach for choosing TH_{ce} and TH_{av}. We first measure the average User Throughput (UTH), i.e. R_{av}, and the cell-edge UTH, i.e. R_{ce}, in each macro-cell. Then, from the sets of R_{av} and R_{ce} values obtained from all the macro-cells we compute the Cumulative Distribution Function (CDF) of R_{av} and of R_{ce}. Let us refer to R_{av} CDF and to R_{ce} CDF as $F_{av}(x)$ and $F_{ce}(x)$ respectively. Finally, the thresholds TH_{ce} and TH_{av} are set as follows. First, we choose two percentage values $X_{av,\%}$ and $X_{ce,\%}$ of $F_{av}(x)$ and $F_{ce}(x)$ respectively. Second, we set the thresholds as $TH_{av} = F_{av}^{-1}(X_{av,\%})$ and $TH_{ce} = F_{ce}^{-1}(X_{ce,\%})$. With this setting, FSUAH will attempt to enhance the average UTH of the $X_{av,\%}\%$ of macro-cells experiencing the worst R_{av} and the cell-edge UTH of the $X_{ce,\%}\%$ of macro-cells experiencing the worst R_{ce}. In Section III-B we will analyze how different values of TH_{av} and TH_{ce} affect the performance achievable by the algorithm.

III. Simulation Results

A. Simulation parameters and scenario

The FSU algorithm has been tested by means of system level simulation, whose parameters are shown in Table I.

In relation to the FSU algorithm parameters, only TH_{ce} and TH_{av} affects the algorithm performance in terms of throughput gain, while K, L and the timers T_{eval}, T_{reset}, T_{NEW} and T_L rather have some impact on the convergence speed. The values set for the parameters in Table I guarantee the convergence of the algorithm under the condition of the full buffer traffic model and static cell-load (i.e. number of UEs attached to the BSs). The analysis of the algorithm under different simulations models will be object of future studies.

TABLE I: Summary of the parameters used in the simulations.

System model	
Spectrum allocation	50 RBs over 10 MHz centered at 2 GHz, shared by MBSs and LPNs
MBS/LPN TX power	46/30 dBm
MBS antenna pattern/gain	Directive antenna, 3GPP model [8] / 14 dBi
LPN antenna pattern/gain	Omnidirectional antenna / 5dBi
UE antenna pattern/gain	Omnidirectional antenna / 0 dBi
Propagation model	
Channel model	3GPP for HetNet System simulation for outdoor RRH/Hotzone, model 2, case 1, [8]
Shadow fading	8-10 dB
Link-level model	
Link-level abstraction	Upper-bounded LTE Shannon's capacity [9]
Traffic model	
Traffic model	Full buffer
Scenario deployment	
HetNet BS deployment (Macro-cells and pico-cells)	3GPP HetNet Spec. [8]: Macro + outdoor RRH/Hotzone, case 1, configuration 4 for UEs distribution (57 macro-cells, 228 pico-cells, 3420 users).
Number of snapshots	50
User scheduler	
Scheduler	Proportional Fair
(α,β) - MBS	$(1,2)$, $(1,1.2)$, $(1,1)$, $(1.2,1)$, $(1.4,1)$, $(1.6,1)$, $(1.8,1)$, $(2,1)$, $(4,1)$
(α,β) - LPN	$(1,1)$
FSUAH - MBS	
(TH_{av}, TH_{ce}) = [kbps, kbps]	Set 1: $(F_{av}^{-1}(19\%), F_{ce}^{-1}(27\%)) = (250, 60)$ Set 2: $(F_{av}^{-1}(40\%), F_{ce}^{-1}(47\%)) = (300, 80)$ Set 3: $(F_{av}^{-1}(56\%), F_{ce}^{-1}(66\%)) = (350, 100)$
K	4
T_{eval}	0.5 s
T_{reset}	4 s
FSUAH - LPN	
L	5
T_{NEW}	1.2 s
T_L	2 s

B. Simulation results

The performance metrics which are used for testing the FSU algorithm are the cell-edge user throughput R_{ce} and the average user throughput R_{av}. The cell-edge user throughput is defined as the user throughput value corresponding to the 5th percentile of the user throughput Cumulative Distribution Function (CDF). R_{ce} measures the throughput experienced by the so called "cell-edge users", i.e., the users which suffer from bad radio conditions such as low received power or high interference. The FSUAH makes a trade-off between the average user throughput of the LPNs and the cell-edge user throughput of the MBSs, in favor of the latter. We expect that, by limiting the spectrum used by the LPNs, the FSU attenuates the interference of the LPN to the macro cell-edge UEs. Thus, the effect we observe consists of a reduction of the average LPN user throughput on the one hand, and a gain of the macro cell-edge UEs throughput on the other hand.

In this section, we compare the user throughput given by the FSUAH algorithm with the one given by a static frequency allocation scheme, namely reuse 3-1 (i.e. R3-1). In R3-1, the LPNs transmit over the whole 10 MHz band while the MBSs adopt the so-called reuse 3 scheme, i.e., each MBS uses 1/3 of the available spectrum which is orthogonally shared among neighboring MBSs. In contrast, in the FSUAH scheme, the MBSs employ reuse 3 scheme while the spectrum in use by the LPNs is dynamically determined by the FSUAH algorithm (see Section II-A).

In Fig. 5 we can see the effect of the FSU algorithm in terms of R_{ce} enhancement on the MUEs throughput. In fact, the FSU can improve the MUEs R_{ce} by up to 90% compared to R3-1. Moreover, the MUEs also experience an average user throughput gain, which can be up to 24%. This overall enhancement of the MUEs peformance is due to the joint effect of the PF scheduler and of the ICIC operated by the FSUAH algorithm. While the ICIC (implemented by means of spectrum reduction of the LPN) yields a benefit in

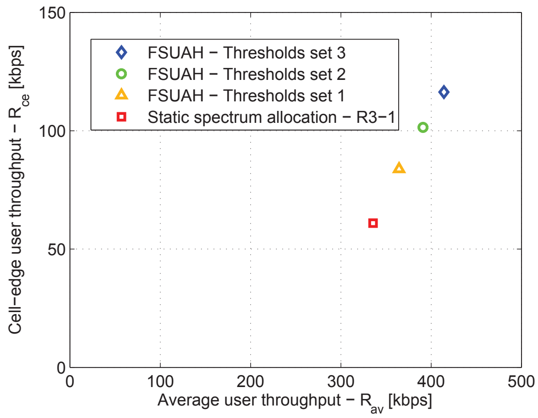


Fig. 5: Macro cell user throughput.

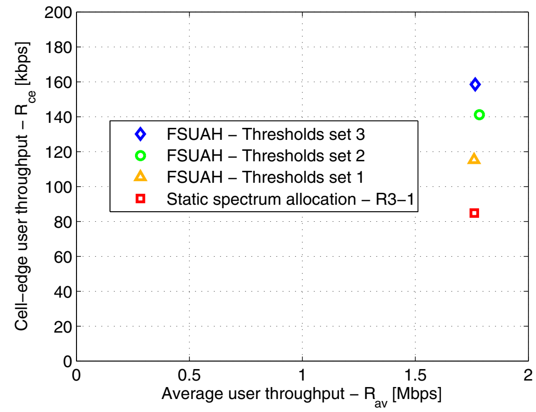


Fig. 6: Overall network user throughput.

terms of interference reduction to the MUEs, the PF algorithm makes this benefit profitable in terms of cell-edge throughput gain. We observe also that, by changing the parameters TH_{ce} and TH_{av}, the FSUAH achieves different throughput values. In general, the higher are TH_{ce} and TH_{av}, the higher is the throughput experienced by the MUEs. However, as aforementioned, the performance gain obtained by the MUEs will be paid in terms of throughput loss for the LPNs users. Hence, increasing the values of TH_{ce} and TH_{av} will not provide an unlimited benefit to the overall network throughput.

As far as the whole network users are concerned (i.e., the UEs served by the MBSs and by the LPNs), we still observe a gain in terms of cell-edge UTH compared to R3-1 (see Fig. 6). This can be explained if we consider the CDF of the overall HetNet user throughput. In fact, in the scenario assumed for our simulation, it turns out that most the network cell-edge users[1] are users served by MBSs. Consequently, improving the MUEs throughput results in a better overall cell-edge user performance.

If we consider the HetNet average user throughput (see Fig. 6), FSUAH does not cause any performance reduction. In fact, the R_{av} gain obtained for the MUEs is sufficient in order to counterbalance the R_{av} losses for the LPNs users. Hence, in the scenario we assumed for the simulation results, FSUAH has been proved to be an effective technique for improving the cell-edge user throughput in HetNets, with a gain which can reach up to 88%.

IV. Conclusions and Future Work

In this paper we have tackled the problem of the inter-cell interference in Heterogeneous Networks (HetNet) and we specifically focused on the interference of the Low Power Nodes (LPN) on macro users. We proposed a distributed algorithm, i.e., FSUAH, which allows the LPNs to make flexible usage of the spectrum, mitigating the harm of the LPN interference to the macro users and providing, at the same time, a good overall HetNet average user throughput. Moreover, FSUAH only requires limited signaling between Macro Base Stations (MBS) and LPNs, meaning low overhead.

By using a joint UE scheduling / Inter-Cell Interference Coordination (ICIC) technique, FSUAH has been shown to increase the macro cell-edge user throughput by up to 90% and to enhance the HetNet cell-edge throughput by up to 88% in the scenario assumed for our simulations. Furthermore, the gain in terms of average user throughput obtained for the MBSs counterbalances the throughput loss of the LPNs, thus containing the overall network reduction in network throughput.

The future work will be focused on the problem of the LPN to LPN interference, in order to improve the performance of LPNs layout within the HetNet

[1] In this case, the term *cell-edge user* does not refer to the fact that the UE is located at the cell edge, but it means that the throughput experienced by the UE is below the value corresponding to the 5th percentile of the the user throughput CDF.

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