On the Performance Gain of Flexible UL/DL TDD with Centralized and Decentralized Resource Allocation in Dense 5G Deployments

Venkatkumar Venkatasubramanian, Matthias Hesse, Patrick Marsch, Michał Maternia
Nokia Networks - Research, Wrocław, Poland
[venkatkumar.venkatasubramanian, matthias.hesse, patrick.marsch, michal.maternia,]@nsn.com

Abstract—**Ultra dense small cell deployments and a very large number of applications are expected to be the essential aspects of the newly emerging 5th generation (5G) wireless communication system. To match the diverse quality of service requirements imposed by a variety of applications, dynamic TDD is proposed as a solution by enabling flexible utilization of the spectrum for uplink and downlink of each cell. In this paper, the system performance of flexible (dynamic) TDD is compared to a fixed portioning of resources for uplink and downlink. Further, the degree of centralization for resource management is investigated in the context of dynamic TDD, because multi-cell scheduling will be important for the design of 5G ultra-dense network architecture. The results show that dynamic TDD is indeed a very promising option for 5G networks, and substantially decreases packet outage delays. We find that the performance gap between centralized and decentralized scheduling is small in case of planned deployments. However, centralized scheduling may be beneficial in certain dynamic TDD deployment scenarios with a very asymmetric access point distribution.**

Index Terms—**5G, RRM, dynamic TDD, centralized resource allocation**

I. INTRODUCTION

Rapidly increasing demand from applications are the main drivers for the mobile network evolution. New generations of wireless systems have appeared approximately every 10 years to satisfy the network requirements; 2G was commercially introduced in 1991, 3G in 2001 and 4G (LTE-A) around 2009. Thus from a pure extrapolation of history the 5th generation (5G) can be expected to be commercialized around 2020.

It is currently envisioned [1] that the key characteristics of 5G networks will be ultra-dense small cell deployments (with cell radii possibly down to a few meters) and very diverse applications with equally diverse requirements ranging from ultra-low latency to Gigabit data rates. For small cell deployments where signals experience small delay spread, it is proposed that a TDD-based air interface can be employed [10], with the option to flexibly assign transmit resources to uplink and downlink communication in each frame. This type of flexible TDD switching between uplink and downlink is also known as dynamic TDD. A dynamic TDD deployment can lead to severe UL/DL cross-interference and impair system performance. In this paper, we hence address two key questions:

- To which extent can a very dense 5G deployment benefit from dynamic TDD despite the interference introduced, and
- To which extent can centralized resource allocation be beneficial in a dynamic TDD 5G scenario.

We investigate two extremes of resource allocation; a completely decentralized scheme which makes independent scheduling decisions in each cell, and uses only interference knowledge from the past and a completely centralized scheme which makes globally optimal scheduling decisions based on a central network entity. Many resource allocation variants are known to exist in between, such as implicit coordination schemes [2,3], where cells do not exchange information but base their decisions on interference measurements, or explicit coordination schemes based on the exchange of information among cells, but still with decentralized decisions, see e.g. [4].

Dynamic TDD has been studied in works such as [5-7]. In [5], user throughput has been evaluated at a system level for a macro based hexagon layout. Simulation results in a network with remote radio units and a central baseband unit performing flexible UL/DL switching in a clustered manner were shown in [6]. In clustered dynamic TDD, remote radio units in a group keep the same time slot allocation pattern that can be adapted over time based on interference conditions and instantaneous traffic demand. In [7], the so called phantom cell concept is investigated in combination with a dynamic TDD scheme and a simplified system level analysis is carried out. In contrast to the cited prior works, this paper is the first to investigate dynamic TDD comparing completely decentralized to fully centralized resource allocation for very dense deployments. We also allow independent switching between uplink and downlink per cell without imposing cell clustering in dynamic TDD.

To answer the key questions stated above, we assume the test case of dense urban information society in the 5G project METIS [1]. This particular test case requires high and uniform performance level for the users of the 2020 information society regardless of their physical location. For our investigations we focus on the indoor part of the test case, as the majority of the traffic originates indoors and this trend is expect to hold in the future [8]. The METIS test case requirement for this test case is to deliver end user data rates of minimum 300 Mbps in DL and 60 Mbps in UL for at least 95% of locations. As a means to achieve the above-mentioned throughput, we consider deploying a large number of Small Cells (SC) in one floor of the dense urban building.

The paper is organized as follows. In Section II, we give a short overview of the evaluation methodology. In Section III, we then introduce the considered 5G concept and numerology. The simulation setup and the simulation results are given in Section IV, and Section V concludes the paper.

II. NOVEL PHY CONCEPT:

We consider an air interface based on MIMO-OFDMA and dynamic TDD. LTE-like power control is assumed in the uplink while the downlink performs no power control, and has a flat power spectral density. The novel OFDMA-based flexible uplink and downlink PHY concept is similar to the proposal in [10] but has been slightly modified in our work for the sake of numerical investigation without impacting the key properties of the concept in [10].

We assume that the 200 MHz bandwidth as in [10] is split into ten bandwidth parts, each of 20 MHz. We then use a 2ms scheduling slot, and capture scheduling performance over 20 MHz bandwidth, while the traffic is assumed to be equally split among the ten 20 MHz bandwidth parts. In addition, for the purpose of resource allocation, we define the size of a resource block to be 1.8 MHz, thus modeling ten resource blocks in 20MHz, and with each resource block comprising of adjacent OFDM sub-carriers. Note that these parameter choices have been done to minimize simulation complexity as much as possible, while still capturing the same extent of scheduling diversity in time and frequency of a system with a potentially higher resource granularity and larger system bandwidth.

The novel PHY concept is a fully synchronized system (access nodes and UEs have aligned frame timing) and each frame carries DL and UL control information along with DeModulation Reference Symbols (DMRS) and data symbols that can be associated either with DL or UL transmission. Control information can be used to carry scheduling decisions, transmission format indications or scheduling request, thus enabling extremely low latency of control plane with respect to scheduling decisions. The novel PHY concept supports flexible uplink and downlink allocation within a TDD time slot of a cell, which we make use in a scheduling slot. This effectively means that depending on the dynamic user traffic demands, the scheduling slot can be switched from uplink direction to downlink direction or vice versa independently per cell. In case the small cells base stations are placed closely, this type of dynamic flexible uplink-downlink switching per cell may potentially lead to severe inter-cell interference situations. We thus describe decentralized and centralized coordination schemes in the next section.

III. MULTI-CELL RESOURCE ALLOCATION SCHEMES

To investigate the extent to which centralized coordination can be beneficial for dynamic TDD, we consider the following two extremes of resource allocation:

A. Standalone decentralized:

The standalone decentralized scheme is a fully decentralized scheme wherein no signaling takes place between small cell access points. In this scheme, a small cell access point makes resource allocation (scheduling) as well as uplink-downlink switching decisions for its users in a selfish manner. To efficiently perform scheduling in scheduling slot # t, it is assumed that the users of a small cell feedback the signal to interference noise ratio (SINR) per resource block based on the estimate from time slot # t-1. Thus, the standalone decentralized scheme is interference-aware based on the SINR feedback. For each resource block in a scheduling slot, a small cell independently simply selects the best link i based on

$$\arg\max_{i\in L} w_i \ R_i \qquad (1)$$

where L is the set of all active links (uplinks and downlinks) for that small cell, w_i is a integer weight equal to the current scheduling slot delay of that link i, which reflects the priority of serving link i, and which can be tailored to any system optimization objective. In this work, the objective is to achieve user fairness in terms of delay performance, and correspondingly w_i is set equal to the maximum delay among all packets waiting to be transmitted on link i. Further, R_i =min(0.88 * log2(1 + $SINR_i$ / 1.333), maxSpectralEff) * bandwidth is the achievable data rate of link i on a particular resource block. We note that for MIMO spatial multiplexing $SINR_i$ is calculated per stream assuming precoding and receiver for singular value decomposition of link i, thus accounting for all interferences on a per stream basis.

B. Fully centralized scheme:

In the fully centralized scheme, the scheduling and uplink-downlink switching decisions are collectively made for a coordination group of neighbouring cells by a central entity. It is assumed that the same entity possesses instantaneous interference information received from all the other small cells which are not in the coordination group. Thus, scheduling decisions are made for all the links within the coordination group and individually for each resource block to maximize

$$\sum_{i\in G} w_i \ s_i \ R_i, s.t\ s_i \in [0,1] \quad (1)$$

In the above equation, G indicates the set of all links in the coordination group, w_i is set equal to the maximum delay among all packets waiting to be transmitted on link i as before while s_i is a binary variable which captures the on-off scheduling decision made for that link on the considered resource. Following additional constraints are imposed while maximizing (2): a) no two links of the same cell are scheduled on the same resource block, b) all resource blocks of a cell in a scheduling slot are allocated only to either uplink or downlink direction. However, muting of a resource block is allowed as part of the scheduling decisions of a cell in order to mitigate inter-cell interference. The computation of R_i and $SINR_i$ is the same as in the standalone decentralized case. Furthermore in the case of MIMO spatial multiplexing, the metric in (2) is computed after deciding the best rank independently for each link for a given combination of links in the search. TABLE 1 below summarizes the assumptions in the schemes.

Rank adaptation and throughput calculation:
Rank adaptation refers to the notion of selecting the number of MIMO streams of a particular link on each scheduling slot and resource block. We make a final rank decision on a resource block basis after resource allocation, thus utilizing the SINR computation after resource allocation. The selection of the number of MIMO streams is made independently for the link that has been scheduled for that small cell. The computation of the optimal number of streams for the link is performed taking into account the interference rejection combining filter.

Throughput calculation: For all the above-mentioned schemes, the final achieved throughput calculation on each link and resource block is made after taking into account: a) the resulting SINRs using interference rejection combining filter taking into account scheduling decisions made in all cells and rank adaptation. The SINR to throughput mapping is again made through the equation $R_i = \min(0.88 * \log2(1 + SINR_i / 1.333), maxSpectralEff) * bandwidth$. Thus we assume perfect link adaptation with an infinite granularity of modulation and coding schemes.

TABLE 1: DESCRIPTION OF SCHEMES

Scheme	**Cells in coordination group**	**Cells in non-coordination group**
Standalone decentralized scheme	Interference information of these cells is taken from last scheduling slot	Interference information of these cells is taken from last scheduling slot
Centralized scheme	Interference information of these cells is available in current scheduling slot. Cells can perform muting.	Interference information of these cells is available in current scheduling slot. Cells do not perform muting.

IV. SIMULATION SETUP

To conduct a system level study we setup an indoor simulation scenario in multiple cells of size 5m x 5m.

TABLE 2: TABLE OF SIMULATION PARAMETER

Parameter	**Default value**
Carrier frequency	2600 MHz
Pathloss model	3GPP small cell path loss model [11], Indoor fast fading model [12]
Wall Penetration loss, UE noise figure	3 dB, 9 dB
Total SC power	-3 dBm in downlink over 20 MHz bandwidth. Uplink SNR target of 42 dB after power control.
UE speed	3 kmph
Antenna configuration	4X4 MIMO. Isotropic
Receiver type	Interference Rejection Combining
Traffic	Poisson with 1 sec inter-arrival time and fixed packet size. UL/DL = 1/4
Number of users	3 users dropped randomly per 5m cell

In a simulation drop, users are dropped in each indoor cell independently. A long simulation run is then conducted for that simulation drop which captures the traffic arrival and resource scheduling for 40 seconds, with a resource scheduling slot being 2ms. Traffic arrival is modeled as Poisson distribution with packets of fixed size and a mean inter-arrival time of 1 second for each user in a cell. The traffic is modeled for the uplink and downlink directions independently. The following scheduling schemes are investigated: a) standalone decentralized with a fixed uplink and downlink scheduling slot split of 1:4, which is tailored to the 1:4 uplink and downlink traffic ratio, b) standalone decentralized with flexible uplink and downlink and c) centralized scheduling for flexible uplink and downlink. Please see TABLE 1 for a short description of the standalone and centralized scheduling concepts.

The key performance indicator is the 99th percentile delay in terms of the serving time delay between the time of packet arrival and time of the completion of packet delivery. The 99th percentile delay has been chosen for capturing worst case delay situations in a given deployment scenario. The statistics of delay are obtained only for the users in the coordinated cells. The following two scenarios are studied: a) uniformly placed small cell base stations and b) a specific random drop case.

A. Uniformly placed small cell base stations (best case)

In this ‘best case’ scenario, it is assumed that the base stations are placed in the center of the rooms, as shown in Figure 1. Simulations are conducted for three different downlink packet sizes: 6400 Kbytes, 12800 Kbytes, 19200 Kbytes and 25600 Kbytes. The uplink packet sizes are a quarter of the respective downlink packet sizes. In all schemes, the packets are assumed to be equally split to ten 20 MHz parts, thus giving 640 Kbytes, 1280 Kbytes, 1920 Kbytes and 2560 Kbytes per 20 MHz respectively.

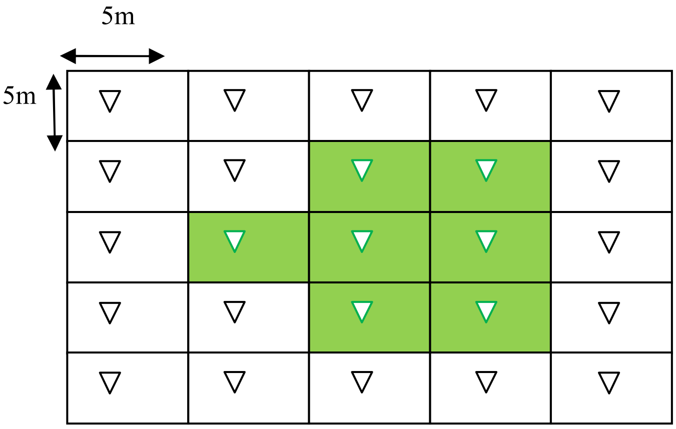

Figure 1. An indoor layout of 25 cells arranged in 5 rows and 5 columns. The figure shows a base station in the center of each cell. The cells performing centralized scheduling are shown in green. Each cell size also corresponds to a room size

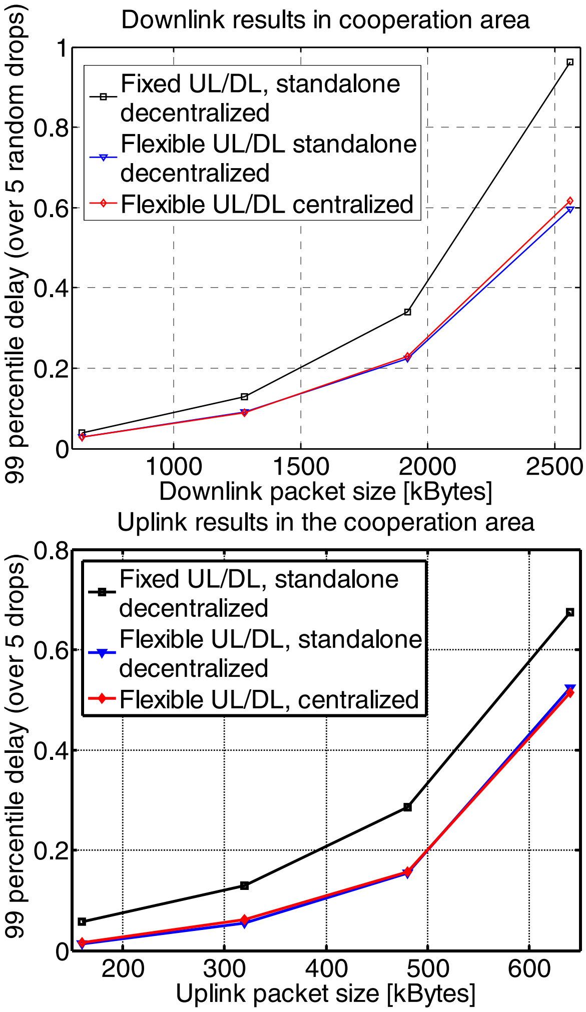

Figure 2. Uplink and downlink packet delay performance for three different packet sizes.

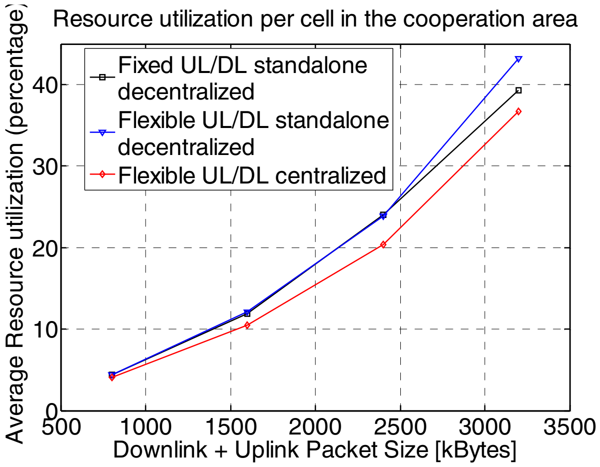

Figure 3. Comparison of resource utilization percentage for different schemes

Figure 2 shows the results for this best case deployment of access points ideally placed in each room for both uplink and downlink and for different packet sizes. In all packet sizes, we see significant performance gain in terms of delay reduction with flexible TDD. In the same figure, results show only a very small performance gap between decentralized and centralized scheduling. This is mainly on account of the interference rejection filters at the receiver and decentralized rank adaptation used in all the schemes. Figure 3 shows the resource utilization for different schemes. It is observed that the centralized allocation consumes the least number of resources because of the optimized allocation and muting of resource blocks. Table 2 summarizes the performance gain of standalone decentralized flexible UL/DL scheduling to a fixed UL/DL scheduling with a UL/DL time split ratio of 1:4. It is observed that flexible UL/DL scheduling provides significant delay reduction both in the uplink and downlink direction for different system loads. It can be seen that as the packet sizes increase, the uplink gain decreases while the downlink gain increases. This behavior can be explained from the fact for fixed TDD scheme the downlink performance deteriorates more rapidly as the system load increases. Flexible UL/DL allocation achieves a similar uplink and downlink delay performance, thus showing an increasingly higher downlink gain as the system load increases.

Table 2. Table of results showing the performance gain of Flexible UL/DL at different system loads

Packet size per 20 MHz	Uplink gain % (gain in terms of delay reduction)	Downlink gain % (gain in terms of delay reduction)
UL 160 Kbytes	71 %	22%
UL 320Kbytes	53 %	26%
UL 480 Kbytes	45%	32%
UL 640 Kbytes	22 %	38%

B. Specific random drop case

In the specific random deployment case, a particular drop of random base station positions and users is considered as in Figure 4. Through this specific case, we intend to characterize the performance of flexible uplink/downlink scheduling in a more challenging setup because of cross-link interference.

In practice random base station drops might be a consequence of unplanned placement of base stations. Thus in Figure 4, it may be observed that cell #12 and cell #8 are potentially problematic cells for the following reasons. Base stations cell #13 and cell #8 are placed in neighbouring rooms close to the wall, and also close to each other. Users of cell #8 are however relatively far from the base station, which may result in low signal to interference noise ratio to the users of this cell, in both uplink and downlink directions. The interfering base stations for cell #8 are cell #13 and cell #3. In the case of cell #12 it is observed that two of the users in the same room as cell #13 actually connect to cell #12 based on higher signal strength, shown as a circle in Figure 4. This means that cell #12 is relatively more loaded with 5 users to serve, and with two of the users experiencing low signal to interference noise ratio because of the additional 3 dB wall attenuation. Thus one could intuitively expect that the performances of cell # 12 and cell # 8 are particularly challenging in this example.

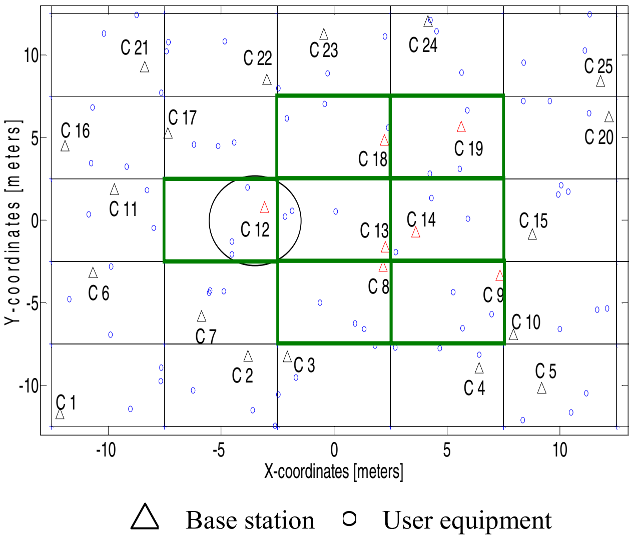

Figure 4- A specific random deployment scenario. C# in red indicates the cooperating base stations. The circle around C12 indicates that it is a more loaded cell serving 5 users

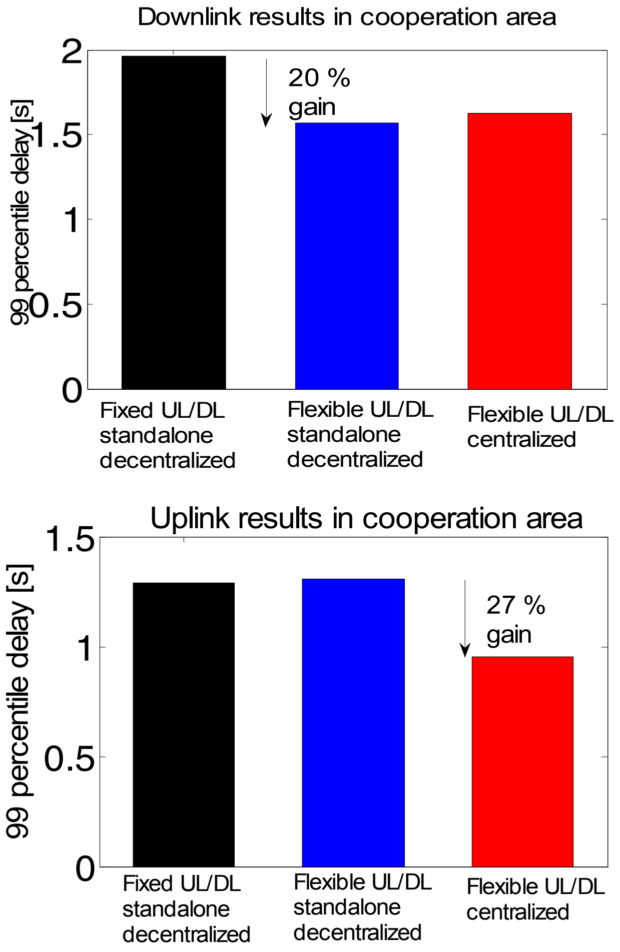

Figure 5. 99 percentile packet delay performance in all the cooperating cells

Here we show results only for the packet size of 25600 Kbytes in downlink and 6400 Kbytes in uplink. Figure 5 shows the results for joint statistics obtained from all the cooperating cells. The following observations are made from Figure 5.

<u>Fixed UL/DL vs Flexible UL/DL standalone scheduler</u>: The flexible uplink/downlink standalone scheduler reduces downlink packet delay from 1.97 sec to 1.57 sec, which is a reduction of 20 %. In this deployment, the absolute downlink delay is larger as compared to the equally spaced 'best case' in Figure 2. Yet the relative performance gain to fixed UL/DL split is still 20% for the downlink. However there is no uplink performance gain with the flexible decentralized scheduler.

<u>Flexible Centralized scheduler</u>: It is observed that centralized scheduler provides more performance benefits as compared to the uniformly deployment 'best case'. The centralized scheduler is seen to be very beneficial in the uplink direction reducing uplink packet delay from 1.31 sec to 0.95 sec, which is a 27 % reduction. This gain comes with only a slight performance sacrifice in the downlink of around 4 %. Thus in this particular random drop case, we observe that centralized scheduling improves both downlink and uplink performance.

To better understand and verify the performance implications of the base station placement, the packet delay performance of individual cells in the cluster is shown in Figure 6.

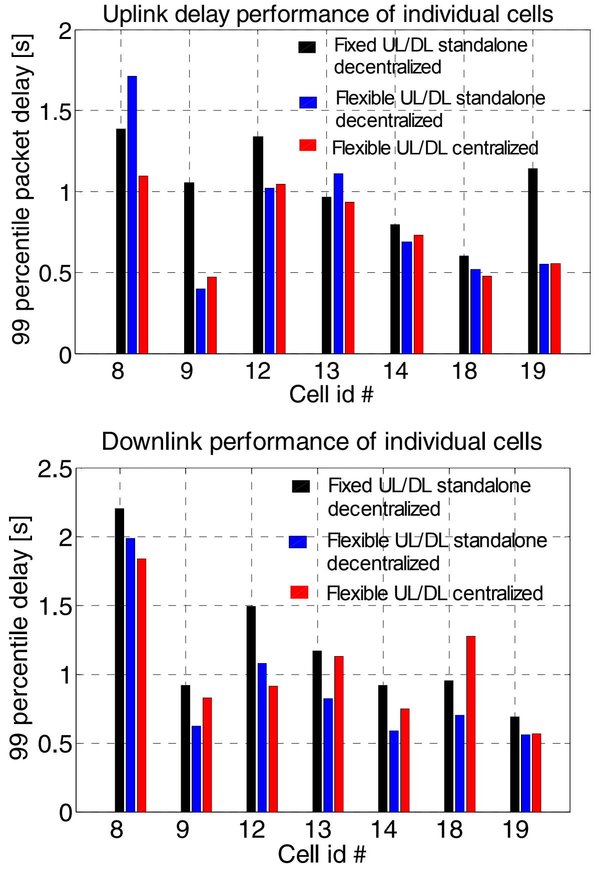

Figure 6. 99 percentile packet delay performance of individual cells in the cooperating cluster

As expected, results confirm that cells #8 and #12 have the worst performance for standalone flexible scheduler. For cell#8, though flexible standalone scheduling provides some downlink performance improvement, the downlink gain comes with an uplink performance penalty of 19%. Flexible centralized scheduler is seen to be particular beneficial for the uplink of cell#8 and provides a 36% gain to flexible standalone scheduler. For cell # 12, it is observed that flexible centralized scheduler improves downlink performance by 28 % as compared to flexible standalone scheduler. At the same time, the centralized scheduler also improves downlink performance by 15% for this cell, as compared to flexible standalone scheduler.

An interesting observation is that for those two problematic cells, fixed standalone scheduler offers the worst performance in either downlink or uplink direction; downlink in the case of cell#8 and uplink in the case of cell #12. Flexible standalone scheduler however offers the worst performance for the uplink of cell#8. Therefore for such particularly challenging examples, centralized flexible uplink/downlink scheduler is seen to be beneficial.

V. CONCLUSIONS AND FUTURE WORK

In this paper, system level studies were conducted to characterize the benefit of dynamic TDD in very dense small cell deployments. We also addressed the question whether tightly coordinated resource allocation would be necessary in dynamic TDD for 5G deployments to mitigate strong inter-cell interference. This interference coordination question is relevant in order to make fundamental design decisions related to 5G system architecture, such as where certain network functionality is located, or which interfaces are needed between access points. The results have shown that dynamic TDD provides substantial system performance improvements especially when access points are ideally placed such that inter-cell interference is apriori minimized. In this case, we find that a decentralized resource allocation would be sufficient if interference mitigation can be done at the receivers in the form of interference rejection combining. However if access points are deployed in a rather uncoordinated manner, the gains from dynamic TDD are reduced, and coordinated resource allocation starts becoming important. This is rather intuitive, as in such deployments very strong cross-interference between uplink and downlink transmissions might occur in few cells.

While the current work has pointed to substantial gains when comparing completely decentralized and fully centralized scheduler in certain deployment scenarios, it is yet to be determined whether centralized RRM should be deployed in 5G systems or whether distributed coordination algorithms would be sufficient. Sophisticated RRM coordination between different cells may incur high complexity and potential scheduling delays. Thus a viable approach may be to utilize decentralized scheduling whenever possible, and only conduct coordination when strong interference cases are detected.

ACKNOWLEDGMENT

Part of this work has been performed in the framework of the FP7 project ICT-317669 METIS, which is partly funded by the European Union. We thank the METIS partners for good collaboration, but the conclusions in this paper are that of the authors and not of the METIS project.

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