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TD-LTE virtual cells: An SDN architecture for user-centric multi-eNB elastic resource management[☆]

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ABSTRACT

This paper introduces mechanisms and algorithms for managing efficiently the resources of Time-Division Long Term Evolution (TD-LTE) networks in a flexible manner enabling (i) dynamic frame alternation at each evolved Node B (eNB) and (ii) forming virtual cells, which allow diverse resource utilization to users residing within regions that can utilize resources from multiple eNBs. Our approach leverages the benefits of Software Defined Network (SDN) paradigm for monitoring network resource utilization and allowing applications or services to request resources. The resources requested by the applications or services can be allocated on-demand by adjusting the Time Division Duplex (TDD) frames in different regions of the geographical area being considered. This can be accomplished by creating virtual cells in the overlapping regions that can customize service for the residing users. A simulation study has been carried out to elaborate the benefits of this approach and the performance enhancements in comparison with the conventional TD-LTE configurations are presented. The results indicate significant performance gains of around 30%–35% considering both UL/DL directions respectively.

1. Introduction

The fast adoption of smartphones and tablets, combined with the widespread deployment of high speed mobile broadband networks, have led to an evolution of diverse mobile services, creating a tsunami of data traffic [1]. Mobile applications such as social media and cloud services have changed the way humans communicate and acquire information from the Internet, being also more interactive due to "always on" features, with higher uplink demands [2]. Equivalently, Machine Type Communication (MTC) applications introduce yet more diverse uplink traffic patterns communicating high amounts of small data, which raise certain Quality of Service (QoS) demands. Hence, emerging mobile applications and services require an increased degree of network resource elasticity to assure effectively different QoS demands.

1.1. Motivation & problem description

Time-Division Long Term Evolution (TD-LTE) supports an unpaired frequency band, wherein uplink (UL) and downlink (DL) are separated in the time domain. Each Time Division Duplex (TDD) frame may support a potential variety of UL/DL ratios, following 7 different configurations as specified in [3], offering resource diversity for emerging data applications. Table 1 illustrates the UL/DL configurations currently supported as per 3GPP TD-LTE. Despite such UL/DL resource flexibility, the initial deployment of TD-LTE involves a synchronous frame configuration across certain network regions with all the cells offering an identical UL/DL ratio in order to avoid cross-slot interference [4]. Such network arrangements effectively limit the advantage of UL/DL resource flexibility since it imposes restrictions among neighboring cells. In response, the 3rd Generation Partnership Project (3GPP) focused on a set of enhancements to address interference and accommodate traffic adaptation [5]. These effort introduce cell specific mechanisms in the sense that UL/DL configuration change takes place in each cell individually in a distributed manner with the goal to optimize uplink and downlink network resources to best serve the local traffic demands, assuming that user equipment (UE) are associated with a single cell at a given time.

Q2 [☆] Fully documented templates are available in the elsarticle package on CTAN.

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Table 1
TD-LTE uplink-downlink frame configurations.

UL/DL configuration	Sub-frame number									
	0	1	2	3	4	5	6	7	8	9
0	DL	S	UL	UL	UL	DL	S	UL	UL	UL
1	DL	S	UL	UL	DL	DL	S	UL	UL	DL
2	DL	S	UL	DL	DL	DL	S	UL	DL	DL
3	DL	S	UL	UL	UL	DL	DL	DL	DL	DL
4	DL	S	UL	UL	DL	DL	DL	DL	DL	DL
5	DL	S	UL	DL	DL	DL	DL	DL	DL	DL
6	DL	S	UL	UL	UL	DL	S	UL	UL	DL

However, neighboring cells may introduce overlapping regions, where UEs can potentially utilize resources, i.e. TDD sub-frames, from different cells provided that interference is considered. When neighboring cells adopt a distinct UL/DL configuration, such overlapping regions may offer yet another UL/DL ratio forming a customized unique type of frames derived from the UL/DL configurations of the involved cells, introducing in this way a notion of cell that is virtual, i.e. with no physical infrastructure (a more detailed description of the virtual cell concept is provided in Section 3.1). The benefits of virtual cells in enhancing the resource allocation efficiency of TD-LTE were shown in [6], which enables mobile operators to match closer the offered resources with the service demand. Nevertheless, such analysis focused on demonstrating the performance potential of a virtual cells considering a simple scenario of two base stations or evolved Node Bs (eNBs) in 3GPP terminology.

1.2. Contributions

This paper introduces the mechanisms and network management architecture that can facilitate a broader adoption of virtual cells in TD-LTE networks. It encounters also a closer coordination with cell specific adaptive UL/DL frame re-configuration, i.e. enforcing a selected frame re-configuration on particular cells that may enable an improved virtual cell formation, without compromising the performance of other existing users. Considering the network management architecture, this paper adopts the SDN paradigm to facilitate a fine-grained network resource control based-on a global network view, which also enables application and service providers to acquire QoS and resources via the Application-Controller Plane Interfaces (A-CPI) [7]. Although this later feature is not explicitly explored into this work, the proposed mechanisms can accommodate on-demand resource allocation, which reflects the generic case for OTT resource acquisition via the use of the A-CPI.

Based-on this information, and on knowledge of incoming requests from application and service providers, the SDN controller: (i) feeds an algorithm, which identifies the TD-LTE frame configuration for particular eNBs inside the radio access network and (ii) enforces such a new TD-LTE frame configuration at the selected eNBs allowing in this way a more efficient resource management with the option of enabling virtual cells at desired locations.

In particular, the contributions of this paper are:

- A framework for adopting the SDN paradigm for virtual cells considering a macro cellular deployment scenario, where SDN is used to enforce a re-configuration of the UL/DL TDD ratio at particular eNBs, in order to secure resources for virtual cells. Such resources can serve the required traffic demands as close as possible resolving pseudo congestion, without increasing the interference for all other users beyond a certain limit, i.e. making sure that the overall impact of virtual cells is positive.
- The introduction of an SDN network management architecture that supports the monitoring and dynamic control of virtual cells based-on observed traffic demands.
- The analytical logic for allocating resources on virtual cells considering the amount of resource blocks that enhance UEs' resource allocation and network utilization without compromising the performance of other existing users.
- The algorithm for forming virtual cells and enforcing TD-LTE frame re-configuration on selected cells in order to overcome pseudo-congestion.
- The simulation study that provided a comparative evaluation of the proposed virtual cell solution with the cell specific adaptive re-configuration and with the simple static configuration.

The rest of the paper is organized as follows. Section 2 documents the related work. Section 3 introduces the virtual cell concept, elaborates the network management architecture based-on the SDN paradigm, analyzes interference in TD-LTE and defines effective capacity allocation for virtual cells, before presenting the TD-LTE elastic resource management algorithm. Section 4 presents the simulation setup and analyzes the results. Finally, Section 5 concludes our work and provides further research directions.

2. Related work

In the initial TD-LTE deployments, each cell supported an identical TDD frame that matches best the estimated long term UL/DL traffic demands. This synchronized operation across a network region of eNBs offers a uniform constant UL/DL ratio providing a simple solution for avoiding cross-slot interference. Efforts towards improving the flexibility of such a scheme concentrate on handling interference, which is the fundamental constraint against a dynamic form of TD-LTE in where each cell is capable to adopt a different TDD frame and change it over time based-on evolving traffic demands. In [4,8], the challenges and benefits for adopting a flexible TD-LTE scheme are analyzed focusing on mechanisms that dynamically change the UL/DL configuration on each cell at different timescales to match the UL/DL traffic demands accommodating power control and/or clustering mechanisms for avoiding interference. Our proposal adopts a dynamic TD-LTE scheme, employing power control mechanisms to accommodate interference mitigation.

Recent advancements on TD-LTE investigate mechanisms that aim to optimize the UL/DL ratio selection for each eNB, considering a variety of different constraints. An asymmetric assignment of UL and DL is investigated in [9], which aims to reshape interference channels exploiting efficiently the available backhaul resources. In [10], a cooperative decentralized mechanism is introduced that provides a local optimal solution considering instantaneous data rate conditions and traffic demands, which are exchanged via reliable low-rate signaling among neighboring cells. An alternative approach that aims to minimize the information exchange among neighboring cells by enabling eNBs to perform autonomously an UL/DL ratio optimization based-on a game theoretic method is introduced in [11], considering UL/DL delays in relation with traffic load, interference and flow-level dynamics.

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Optimizing further the selection of the TDD frame considering the evolving Quality of Service (QoS) demands in terms of bit rate guarantees and packet delay is elaborated in [12]. The potential gains in throughput and reduced packet delays once each TDD slot is freely assigned as UL or DL instead of using one of the 7 predetermined TDD frames is explored in [13], assuming the use of Interference Rejection Combining (IRC) capable receivers to handle cross-slot interference.

An SDN framework for elastic resource sharing among a Frequency division Duplex (FDD) and TDD system enhancing flexibility and the efficiency of network resource management is described in [14]. This paper also adopts an SDN network management paradigm, but instead it concentrates on network programming aspects, i.e. forcing a TDD ratio re-configuration for providing TDD virtual-cells, enhancing the user service performance and the network resource utilization.

However, such proposals consider individual eNBs focusing on the means of providing a dynamic UL/DL ratio in an autonomous way considering a various optimization parameters. Unlike these cell centric approaches, our proposal stretches beyond a single cell, i.e. local optimization, exploiting efficiently the resource diversity within overlapping cell areas as elaborated in [6]. This enables UEs to utilize sub-frames from multiple eNBs, i.e. forming virtual cells that offer customized TDD frames, which match best their UL/DL traffic demands. Performing radio resource management that combines dynamic TDD re-configuration with virtual cells in a distributed manner is suboptimal. Hence, centralized intelligence is recommended for efficient interference mitigation considering traffic dynamics.

Our virtual cell concept is also employed in [15], which adopts the SDN paradigm to enhance the user QoE considering the application performance characteristics in a pico-cell environment. In particular, the QoE assessment function at the eNB contacts the SDN controller when it identifies users that suffer a QoE degradation, which can be benefited from utilizing resources from multiple eNBs forming virtual cells. Unlike [15], this paper provides network programming operations, enforcing a TD-LTE frame re-configuration at particular eNBs for the sake of enabling a virtual cell with a specific customized UL/DL ratio and provides an algorithm to address this goal.

A similar approach referred to as V-Cell, offers a combination of heterogeneous radio resources, i.e. macro-cells, picos and femtos, as a resource pool to UEs, which perceive such an access as a logical single macro-cell [16]. The network resource management is performed by an SDN controller, which maintains a logical global view of the underlying network in order to efficiently schedule resources across the entire pool of physical radio elements.

An equivalent SDN-based Radio Access Network (RAN) management architecture that relies on abstracting the RAN resources and using them as a single virtual wireless access is also analyzed in [17], which also provides more details about the SDN controller including the main associated functions and the control plane mechanisms. Effectively such components enable RAN programmability as considered in [18], which analyzes the SDN impact of separating the control and data planes in simplifying the management of heterogeneous networks, considering mobility and QoS-aware network operation. In fact, the SDN architecture offers the N-API towards application providers facilitating on-demand QoS provision. In this paper a similar SDN paradigm is employed offering RAN programmability, which is realized by enabling a unified control for provisioning a dynamic TDD frame configuration at selected eNBs with the potential of forming virtual cells based-on the user resource demand. Whilst our focus is on network programmability based-on network measurements and resource utilization, the proposed SDN architecture may potentially offer a customized UL/DL ratio upon a request via the N-API, allowing applications to program the network and provision resources for particular services within certain times. Such a feature may advance the network customization offering flexibility, scalability and ease in deployment of new services and enhanced performance of TD-LTE systems.

3. Elastic radio resource management mechanisms for TD-LTE

This section describes the main components for realizing the proposed elastic TD-LTE resource management mechanisms. Initially, the SDN architecture that manages the TD-LTE network is described, followed by the resource management logic for creating virtual cells and the TD-LTE resource allocation algorithm for re-programming the network configuration.

3.1. Virtual-cell concept

The concept of virtual cell allows users to utilize subframes from multiple eNBs, enabling the formation of a customized virtual frame by deriving specific subframes from different eNBs that can reflect best the user UL and DL transmission demands [6]. The flexibility offered by this feature allows the resolution of pseudo congestion, while enhancing the user performance. Pseudo congestion refers to the phenomenon wherein adequate resources exist in a TD-LTE eNB, but in the opposite transmission direction than the user demand. Such a technique could also be beneficial for the users that are outside the virtual cell region as it could free up additional resources for them to achieve their desired QoS. In addition, this technique not only exploits the spatial domain of conventional load balancing but also the time domain, to dynamically configure the cell setup.

The adjacent cooperating eNBs in virtual cell concept appears to be as one logical cell with each eNB offering a different UL/DL configuration. This provides the capability to support multiple and diverse applications within smaller geographical regions. It is worth noting that the UEs cannot utilize UL and DL sub-frames within the virtual cell region at the same time because of device and hardware restrictions. The process of utilizing sub-frames from different eNBs requires enhanced mechanisms to synchronize UEs and align their transmit/receive modes accordingly. Therefore synchronization is required between the eNBs involved in the virtual cell formation to ensure that the data towards and from the UE appears as a single stream hence the virtual cell requires additional signaling mechanisms for control purposes. A simple example of the virtual cell concept is illustrated in Fig. 1 where, a UE residing within the virtual cell region is utilizing UL resources from eNB A and DL resources from eNB B to match its traffic demand. Specifically, the UE is utilizing UL resources from eNB A and DL ones from both eNB A and eNB B, creating in this way a new virtual frame as indicated in Fig. 1, which is capable to resolve pseudo congestion [19] that would otherwise be caused if the UE would solely utilize the resources from either eNB A or eNB B.

3.2. SDN-based network management architecture

The SDN-based system aims to perform network resource management and TD-LTE programming considering adjustments on selected TDD frames forming also virtual cells. The objective is to abstract the control plane from individual eNBs and logically centralize it, resulting in a collective resource management and control of eNBs' resources, as described in [17]. To accommodate such a vision, the OAM accompanied by the Data-Controller Plane Interfaces (D-CPI), can facilitate periodic or on demand RAN state updates in order to help the SDN controller to form a global network view [7]. In particular, the OAM can provide the SDN controller with RAN topology information, UL and DL load and Key Performance Indicators (KPIs), e.g. handover failures, latency, throughput, etc. as

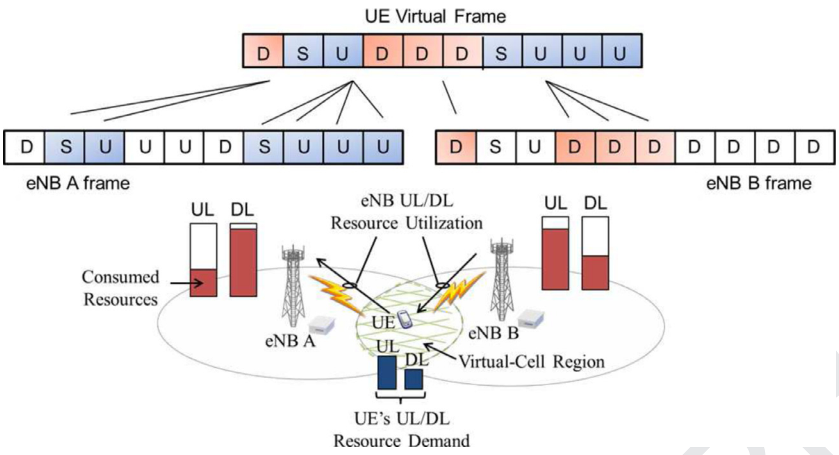

Fig. 1. A simple example of the virtual cell concept.

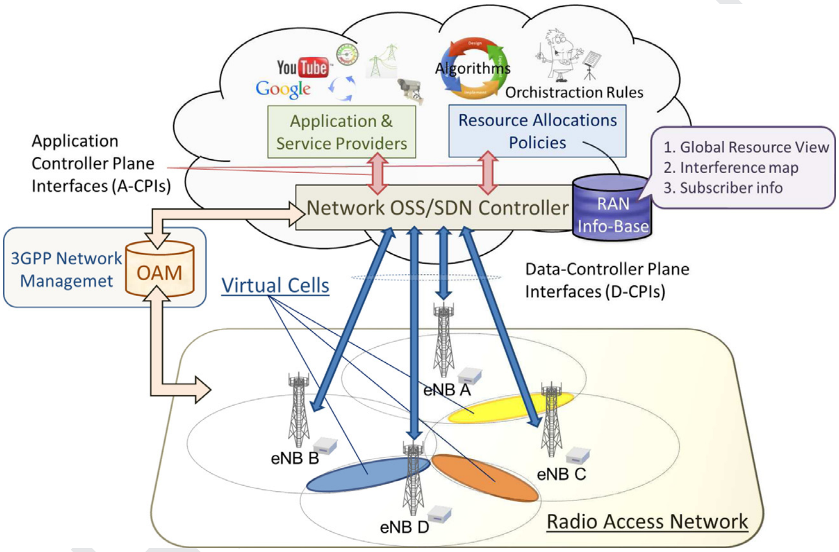

Fig. 2. SDN-based network architecture.

specified in [20]. The D-CPI, may additionally provide the SDN controller with certain information related to specific rules including monitoring, such as interference levels and the TD-LTE frame configurations per eNB [21].

With a global visibility across the RAN, the SDN controller can enhance the resource allocation, enabling virtual cells by adjusting dynamically the power and subcarrier allocation profile of each eNB. The SDN controller can assess the impact of a TDD frame reconfiguration in the overall performance of the entire network and selectively enforce certain TDD frame changes at specific RAN locations, which otherwise will not be performed through the use of the local adaptive TD-LTE [4]. In addition, the scalability is improved since TD-LTE re-configuration algorithms that may require a significant amount of data can be executed at the SDN controller rather than at eNBs, which have limited computational capacity, avoiding also extensive distributed signaling among multiple eNBs and backhaul elements, while assuring stability.

When the SDN controller is notified or it identifies the need for a change in the TD-LTE arrangement, it ties to determine if a TD-LTE frame re-configuration on particular eNBs and/or the use of virtual cells, can enhance the resource utilization. To accomplish this the SDN controller is making use of the global network state provided by the RAN info-base and execute the provided algorithm and network orchestration policy. It should be noted that the algorithmic logic and orchestration policy can potentially be programmed via the N-API or Application-CPI (A-CPI), where operators have this degree of freedom and flexibility. Once, the SDN controller determines the new TD-LTE resource allocation solution it communicates the essential changes on the TD-LTE configuration back to the corresponding eNBs via the C-DPIs. Effectively, this may alter the transmission power associated with particular TDD sub-frames to assure interference mitigation among neighboring eNBs and facilitate the creation of virtual cells. Whilst left for further study and only considered here for the architecture completeness, the SDN controller may also allow application providers to program the RAN via A-CPI, enabling QoS provision for particular services. An overview of the SDN architecture that elaborates the main elements of the elastic TD-LTE mechanism including their interaction is provided in Fig. 2.

Since, network traffic interference conditions may fluctuate significantly even for short time periods, especially within the relatively small virtual cell regions, due to user mobility, additional distributed mechanisms should be considered. Such mechanisms may relax the workload on the SDN controller, allowing longer time scale tolerance on the TD-LTE configuration decisions provided to the RAN. Hence, local radio resource adjustments should complement the ones provided by the SDN controller as long as no neighbor eNBs are affected.

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3.3. SINR analysis and effective capacity allocation for TD-LTE virtual cells

TD-LTE systems are particularly sensitive to interference, especially when neighbor eNBs follow a different UL/DL ratio, e.g. in the case of cell specific adaptive re-configuration and virtual cell, due to cross-slot interference. Cross-slot interference is caused by eNBs that directly interfere or among UEs in close proximity, which communicate in the opposite transmission direction [22]. Due to physical limitations of the radio frequency front end at eNBs and UEs, there is the need to avoid such cross-slot interference. In our proposal we achieve this via the use of power control and ensure that the interference introduced cause negligible degradation in the user performance by computing the SINR considering the aforementioned interference phenomena.

The SINR is computed for each user associated with a particular eNB over the RBs assigned to it for transmitting the data. The expression for SINR for the UL and DL direction is given by:

$$\gamma = \frac{P_{rx}}{I + N_0} \tag{1}$$

where, P_{rx} is the received power in UL or DL direction respectively, I is the interference power and N_0 is the noise power. In the UL direction, UEs that transmit data towards their serving cell over the RBs assigned by the MAC scheduler, may possibly employ the same subset of RBs that are utilized in the neighbor cell at the same time. Therefore, the interference experienced by the received signal at the serving cell over the RBs should be considered while computing the SINR expression in the UL direction. In the DL, all transmissions on the same subset of RBs coming from other eNBs are considered while computing SINR expression. The P_{rx} in UL or DL is given by:

$$P_{rx} = P_t.\tau.\left(\frac{d_0}{d}\right)^{\phi}.\psi \tag{2}$$

where, P_t is the transmit power in UL or DL, τ is a unitless constant, which depends on the antenna characteristics and average channel attenuation, d is the distance between the transmitter and receiver and d_0 is a reference distance for the antenna far field [22,23]. The pathloss exponent is given by ϕ and ψ is a Gauss-distributed random variable representing the shadowing effects in propagation with mean zero and variance σ_{ψ}^2. The interference power is given by:

$$I = \sum\nolimits_{l\neq o} P_{t,l}.\tau_l.\left(\frac{d_{0,l}}{d_l}\right)^{\phi_l}.\psi \tag{3}$$

While deriving the SINR expression for the cell specific adaptive re-configuration and virtual cell considering the UL and DL directions, the cross-slot interference,that may arise, should also be taken into account. The SINR expression for both cases in the UL direction for a user i connected to a cell l with respect to a set of neighboring cells J_l can be expressed as:

$$\gamma_{i,l}(UL) = \frac{P_{UL}}{\sum_{k}^{J_l} I_{DL}(l,k) + \sum_{k,k\neq l}^{J_l} I_{UL}(l,k) + N_0} \tag{4}$$

where, $I_{DL}(l,\, k)$ is the interference power of the DL signal in the neighbor cell $k \in J_l$ observed at the serving cell l, $I_{UL}(l,\, k)$ is the interference power of the UL signal in the neighbor cell $k \in J_l$ observed at the serving cell l and N_0 is the noise power. The equivalent SINR expression in the DL direction is:

$$\gamma_{i,l}(DL) = \frac{P_{DL}}{\sum_{k,k\neq l}^{J_l} I_{DL}(l,k) + \sum_{k}^{J_l} I_{UL}(l,k) + N_0} \tag{5}$$

where, $I_{DL}(l,\, k)$ is the interference power of the DL signal from the neighbor cell $k \in J_l$ measured at the UE i in the cell l and $I_{UL}(l,\, k)$ is the interference power of the UL signal from an active UE operating in the neighbor cell $k \in J_l$ at the UE operating in the serving cell l. The likelihood of forming virtual cells depends on traffic load conditions in the UL and DL directions and on the resource availability from neighboring cells, i.e. similarly to the likelihood of providing load balancing. A virtual cell is merely a more advanced means of performing load balancing in a TD-LTE network, since a user can utilize partial resources from a neighbor cell in a particular transmission direction.

For enabling an efficient virtual cell formation, there is a need for a mechanism to ensure that the resource gain for a particular cell is does not result in starving the users in another cell, i.e., there is no negative impact of virtual cell configuration on the users of neighbor eNB from where the resources are taken. To assure this capacity gain and loss calculations are performed considering the effective bandwidth model presented in [24]. Regarding the size of a virtual cell, there is no specific size in terms of a geographical area. Virtual cells are user-centric, with the number of users served via a virtual cell varying depending on the traffic load and the users SINR at particular locations and times, influencing in this way the physical size. For calculating the throughput on the serving link as well as the potential virtual neighbor cell. The capacity of the link S [b/s/Hz] in UL and DL is:

$$S_{\mathrm{i,k}} = \min\left(B_{\mathrm{eff}}\cdot\log_2\left(1+\frac{\gamma_{\mathrm{i,k}}}{\gamma_{\mathrm{eff}}}\right), S_{\mathrm{eff}}\right), \tag{6}$$

where B_{eff} is the bandwidth efficiency, γ is the link-level SINR, and γ_{eff} the SINR efficiency, for a system with maximum spectral efficiency S_{eff}. For borrowing resources from neighbor eNBs and creating virtual cells, we consider a capacity gain and loss metric, similar to the one considered in [25]. Let R_{k} be the total available resource blocks at a neighbor eNB k, β be the percentage of available resources that can be borrowed, and $\gamma_{\mathrm{i,\,k}}$ be the SINR experienced by the user i with eNB k. The capacity gain by borrowing resources and creating a virtual cell, C_{g} [b/s] in UL/DL is given by:

$$C_{\mathrm{g}} = R_{\mathrm{k}}\cdot\beta\log_2\left(1+\gamma_{\mathrm{i,k}}\right) \tag{7}$$

and the capacity loss C_{l} [b/s] for the mean user m of eNB k, having SINR $\gamma_{\mathrm{m,\,k}}$ (UL/DL), due to the user i borrowing the resources is given by:

$$C_{\mathrm{l}} = R_{\mathrm{k}}\cdot\beta\log_2\left(1+\gamma_{\mathrm{m,k}}\right) \tag{8}$$

The virtual cell is created with eNB k for user i, if $C_{\mathrm{g}} > \delta C_{\mathrm{l}}$. This condition ensures that the resource borrowing is done only when there are some capacity gains for the congested cell of UE i, and is limited by the factor $\delta \in [0,\, 1]$. The mean user SINR, $\gamma_{\mathrm{m,\,k}}$ for eNB k having N_{k} UEs, is given by:

$$\gamma_{\mathrm{m,k}} = \frac{\sum_{u=1}^{N_{\mathrm{k}}}\gamma_{\mathrm{u,k}}}{N_{\mathrm{k}}} \tag{9}$$

The virtual cell creation decision is taken per UE, depending on its link quality with its serving cell having congestion, as well as the strongest neighbor cell. For a user i, with eNB o as its own cell, i.e. the cell that experience congestion, having $R_{\mathrm{i,\,o}}$ resource allocated to it and eNB k as the virtual cell with $R_{\mathrm{i,\,k}}$ resources borrowed from the cell, the total link level capacity of the user, C_{i} [b/s] in UL/DL is given by:

$$C_{\mathrm{i}} = \sum_{c=i,k} R_{\mathrm{i,c}}\cdot S_{\mathrm{i,c}} \tag{10}$$

If the capacity gain and loss condition is satisfied only then the required resources β are borrowed to resolve the congestion, otherwise the users are served via the standard cell specific adaptive re-configuration process. It should be noted that our virtual cell proposal assumes the use of two base stations since the proposed virtual cell concept can be built on the top of dual connectivity as

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Table 2
List of variables used in the pseudo-algorithms.

Notation	Description
$l \in L$	Cell belonging to a set of total network cells L
$o \in O$	Cell belonging to a set of congested cells $O \in L$
$l[tp]$	UL or DL average active user throughput in cell a $l \in L$
$tp(i)$	UL or DL active user i throughput
tp_{th}	UL or DL throughput threshold
T_c	Time duration beyond which a cell with continuously limited resource is declared as congested
$k \in J_o$	Cell belonging to a set of neighboring cells J_o of a congested cell o
$x_{(J_o)}$	Cell belonging to J_o with maximum R_k in UL or DL direction
R_k	Total available resources in a cell k
R_{req}	Amount of resources needed to resolve congestion in o
β_l	Available UL or DL resources of cell l that can potentially be used to form a virtual cell
$F[l]$	Current TD-LTE frame of cell $l \in L$
S_F	Set of sub-frames that belong to a TD-LTE frame $F[l]$
$F_n[l]$	New TD-LTE frame for cell $l \in L$
$i \in U_o$	User belonging to a sorted set of active users U_o in an incremental $\gamma_{i,\,o}$ order, residing in a congested cell o
$vCell_{UE}$	Set of UEs assigned to the virtual cell region
$r_{x_{(J_o)}}(i)$	Resources allocated to user i once associated with a virtual cell borrowed from the selected neighbor cell $x_{(J_o)}$
$\gamma_{i,\,o}$	SINR experienced by an active user i residing in a congested cell o
$\gamma_{i,\,k}$	SINR experienced by an active user i from a neighbor cell k
$\gamma_{m,\,k}$	SINR experienced by the mean active user of a neighbor cell k
C_g	Capacity gain
C_l	Capacity loss

documented in [26], which introduces the concept of bearer split concept involving two base stations.

3.4. Elastic resource management algorithm for TD-LTE

The resource management algorithm aims to perform an elastic capacity allocation in UL or DL direction regulating the formation of virtual cells in order to enhance the users' performance and resolve potential pseudo-congestion problems. The algorithm also intends to maximize the throughput of low SINR users without causing negative effects on the QoS of other users, residing within the region of the serving cell or the surrounding neighboring cells.

The algorithm is executed at the SDN controller taking as input the global view of the network and the set of congested cells, i.e. cells that experience congestion for a time duration $t > T_c$, where T_c is the time period beyond which a cell with continuously limited resources is declared as congested. The notion of congestion for the best effort traffic, where there is no strict service quality requirement, is accounted considering the minimum achieved throughput. The minimum throughput thresholds in UL and DL directions are used to detect congestion and trigger the algorithm in order to assess and resolve the situation. The throughput thresholds in UL and DL are selected considering the service delay, which should be upto 300 ms according to [27] for the best effort traffic. Our algorithm considers the effective capacity, i.e. capacity gain and capacity loss constraints, which are dependent on users location, so it takes into account the user position and potentially it can take into account user movements. Considering user mobility we clarify, that virtual cells do not intend to serve users with high mobility but rather stationary and low mobility such as pedestrian users.

The algorithm initially examines the set of congested cells with the objective of forming virtual cells, selecting the optimal neighboring cell, which can offer the desired amount of resources. During this process the algorithm may also enforce a TD-LTE frame reconfiguration to resolve potential pseudo-congestion, if that allows adequate resources for forming virtual cells.

Once the cells that comprise the virtual cell region are selected, the algorithm examines which users should be associated with such a virtual cell region considering the capacity gain and capacity loss. The variables used throughout the proposed algorithm are summarized in Table 2.

Algorithm 1 Forming Virtual Cells: Neighbor Cell Selection.

```
1: $O \Leftarrow$ set of cells $l \in L$ with $l[tp] \leq tp_{th}$ for time duration $t \geq T_c$;
2: foreach $o \in O$
3:    $J_o \Leftarrow$ neighbor cells $l \in L$;
4:    $x_{(J_o)} \Leftarrow$ neighbor cell $k \in J_o$ with max$(R_k)$ in UL or DL congestion direction;
5:    if $\beta_{x_{(J_o)}} \geq R_{req}$
6:       call Algorithm 2;
7:    else
8:       $x_{(J_o)} \Leftarrow$ neighbor cell $k \in J_o$ with max$(\sum_{UL/DL} R_k)$;
9:       //check and enforce TD-LTE frame re-configuration on $x_{(J_o)}$
10:      $F[x_{(J_o)}] \Leftarrow$ current $x_{(J_o)}$ TD-LTE frame configuration;
11:      while $x_{(J_o)}[t_p] > tp_{th}$
12:         $F_n[x_{(J_o)}] \Leftarrow F[x_{(J_o)}]$ with min$(S_F)$ re-configured in congestion direction;
13:         if $x_{(J_o)}[t_p] \leq tp_{th}$
14:            break;
15:         else
16:            $F[x_{(J_o)}] \Leftarrow F_n[x_{(J_o)}]$;
17:            continue;
18:         end
19:      end
20:      call Algorithm 2;
21:   end
22: end
```

The pseudo-code of the algorithm that concentrates on the cell selection to form virtual cells is illustrated in Algorithm 1. In line 1 the algorithm collects the set of congested cells O. For each congested cell $o \in O$ it identifies its neighbor list J_o, from which it selects the neighbor cell referred to as $x_{(J_o)}$ with the maximum resource availability R_k towards the congestion direction, which may either be on the UL or DL as shown in lines 3 and 4 respectively. Here, the goal is to identify a neighboring cell that can accommodate adequate resources in the desired transmission direction allowing the creation of a virtual cell, which fulfills both UL and DL demands. In this way, the algorithm tries to resolve congestion,

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while making the best use of the current network formation performing no changes to the TD-LTE network configuration.

If the selected cell $x_{(J_o)}$ is able to offer adequate potential resources $\beta_{x_{(J_o)}}$ be used to form a virtual cell satisfying the resource request R_{req} as shown in line 5, a virtual cell is formed and the algorithm then selects the users to associate with such a region, allocating resources based on their location and interference levels, as elaborated in Algorithm 2. Otherwise, the algorithm examines the entire per cell resources irrespective of the transmission direction $\Sigma_{UL/DL} R_k$, with the goal to identify a neighbor cell with the maximum total resource availability and stores its TD-LTE frame as $F[x_{(J_o)}]$ according to lines 8 and 10 respectively. It should be noted that such a neighbor cell even in cases where it cannot fully accommodate the resource request R_{req}, it can still provide the best solution toward resolving congestion, enhancing the average user performance depending on the location and interference conditions.

For such neighbor cell $x_{(J_o)}$, the algorithm in lines 11 to 19 tries to investigate whether enforcing a potential TD-LTE frame reconfiguration may enhance the resource allocation towards the virtual cell, i.e. $\beta_{x_{(J_o)}}$, without compromising the average user performance, ensuring $x_{(J_o)}[t_p] > tp_{th}$. In particular, in line 12 a TD-LTE frame re-configuration is performed, with the new TD-LTE frame $F_n[x_{(J_o)}]$ selected considering the current one, i.e. $F[x_{(J_o)}]$, with the minimum amount of sub-frames S_F re-configured towards the congestion direction. For example if the current configuration $F[x_{(J_o)}]$ employs a DL/UL ratio of 8:1, i.e. configuration 5 in Table 1, and there is a need to enhance the potential of UL resources towards the virtual cell region, then re-configuring the minimum sub-frames towards the UL direction would result in a new TD-LTE frame $F_n[x_{(J_o)}]$ with an UL/DL ratio 7:2, i.e. configuration 4 in Table 1, while in the following iteration if the intention is to enhance UL resources even further would result in a $F_n[x_{(J_o)}]$ with an UL/DL ratio of 6:3, i.e. configuration 3 in Table 1.

A new frame is adopted by the system becoming the current one, continuing such an iterative process provided that the throughput change associated with the average user is still beyond the performance target threshold, i.e. $x_{(J_o)}[t_p] > tp_{th}$, otherwise it ceases, breaking the iterative process, as shown in line 13 to 18. As stated before, once a neighbor cell is selected, potentially with a re-configured TD-LTE frame, a virtual cell is formed and then Algorithm 2 allocate resources towards specific users from the overloaded cell based on their location (i.e. the users residing within the virtual cell region) and interference conditions. The resource allocation is performed based on the user's SINR levels and throughput based on Eqs. (7) and (8).

In particular, Algorithm 2 initiates a set $vCell_{UE}$ to keep a record of the users assigned to the virtual cell region and creates a set of active users residing in a congested cell U_o, which is sorted in an incremental order according to the SINR experienced, $\gamma_{i,\,o}$, as shown in lines 1 and 2 respectively. For each active user starting from the one with the minimum $\gamma_{i,\,o}$, line 3, the algorithm checks if the user throughput $tp(i)$ is below or equal with the predetermined threshold tp_{th} in line 4. The rational for assessing first users with the minimum $\gamma_{i,\,o}$ is to try to improve the performance of users that are more in need since their SINR level is the lowest. For a user with throughput lower than the performance target, i.e. $tp(i) < tp_{th}$, the algorithm examines whether it is beneficial to allocate such a user to the virtual cell region, in lines 4 to 14. To accomplish this, initially the algorithm in lines 5 and 6 calculates the capacity gain C_g and capacity loss C_l, as elaborated in Section 3.3.

In case the capacity gain is greater than the capacity loss, the user is allocated in the virtual cell region. The algorithm adds that user to the $vCell_{UE}$ set and subtracts the allocated resources $r_{x_{(J_o)}}(i)$ from the potential resources $\beta_{x_{(J_o)}}$ that can be used within the virtual cell region. Otherwise, the user remains constant, i.e. uninterrupted, and the algorithm continues with the next user until all users $i \in U_o$ are considered or the $\beta_{x_{(J_o)}}$ resources are exhausted. The algorithm returns the set of users $vCell_{UE}$ that should be allocated in specified virtual cell regions, the neighbor cells involved and any enforced TD-LTE frame re-configuration associated with a particular neighbor cell. It is also worth noting that the users allocated resource from the virtual cell region could potentially free up resources for other users residing outside the virtual cell region and help towards resolve congestion in the problematic cell, thereby improving the overall network performance.

Algorithm 2 Allocating Users to the Virtual Cell Region.

```
1:  $vCell_{UE} \Leftarrow \emptyset$;
2:  $U_o \Leftarrow$ sorted set of active users in an incremental $\gamma_{i,o}$ order;
3:  foreach $i \in U_o$ starting from $i$ with min($\gamma_{i,o}$)
4:      if $tp(i) < tp_{th}$
5:          $C_g \Leftarrow R_k \cdot \beta_{x_{(J_o)}} \log_2(1+\gamma_{i,k})$;
6:          $C_l \Leftarrow R_k \cdot \beta_{x_{(J_o)}} \log_2(1+\gamma_{m,k})$;
7:          if $C_g > C_l$
8:              //allocate user i in the virtual cell region
9:              $vCell_{UE} \Leftarrow vCell_{UE} \cup i$;
10:             $\beta_{x_{(J_o)}} \Leftarrow \beta_{x_{(J_o)}} - r_{x_{(J_o)}}(i)$;
11:         elseif $C_g \le C_l$
12:             //do not interrupt user i
13:             continue with next the user from $U_o$;
14:         end
15:     end
16:     if $\beta_{x_{(J_o)}} \le 0$
17:         break foreach loop;
18:     end
19: end
```

Table 3
System simulation parameters.

Parameter	Value
eNB ISD	500 m
System bandwidth	10 MHz
Duplexing scheme	TDD
eNB Max Tx power	46 dBm
eNB Antenna gain	15 dBi
UE Total Tx power	23 dBm
UE Antennal gain	0 dBi
Path loss model	$128 + 37.6\ log_{10}$(R), R in Km
Spectral efficiency, Seff	4.0
Number of RBs, NRB	50
PRB size, RBs	180 kHz
Bandwidth efficiency, Beff	0.65
SINR efficiency, SINReff	0.95
File size (FS)	0.5MB
tp_{th}	(0.5/1) Mbps

4. System simulation and result analysis'

We carried out event based system level simulations in Matlab to evaluate the performance of the proposed SDN based elastic resource management solution that introduces virtual cells in TD-LTE networks. We considered a standard 19-site and 3-sector hexagonal network layout, altogether forming 57 cells and adopted the evaluation methodology defined in [28]. The motivation behind our experimentation is to compare our virtual cell proposal with the existing standards study performed in [5] and the basic TDD

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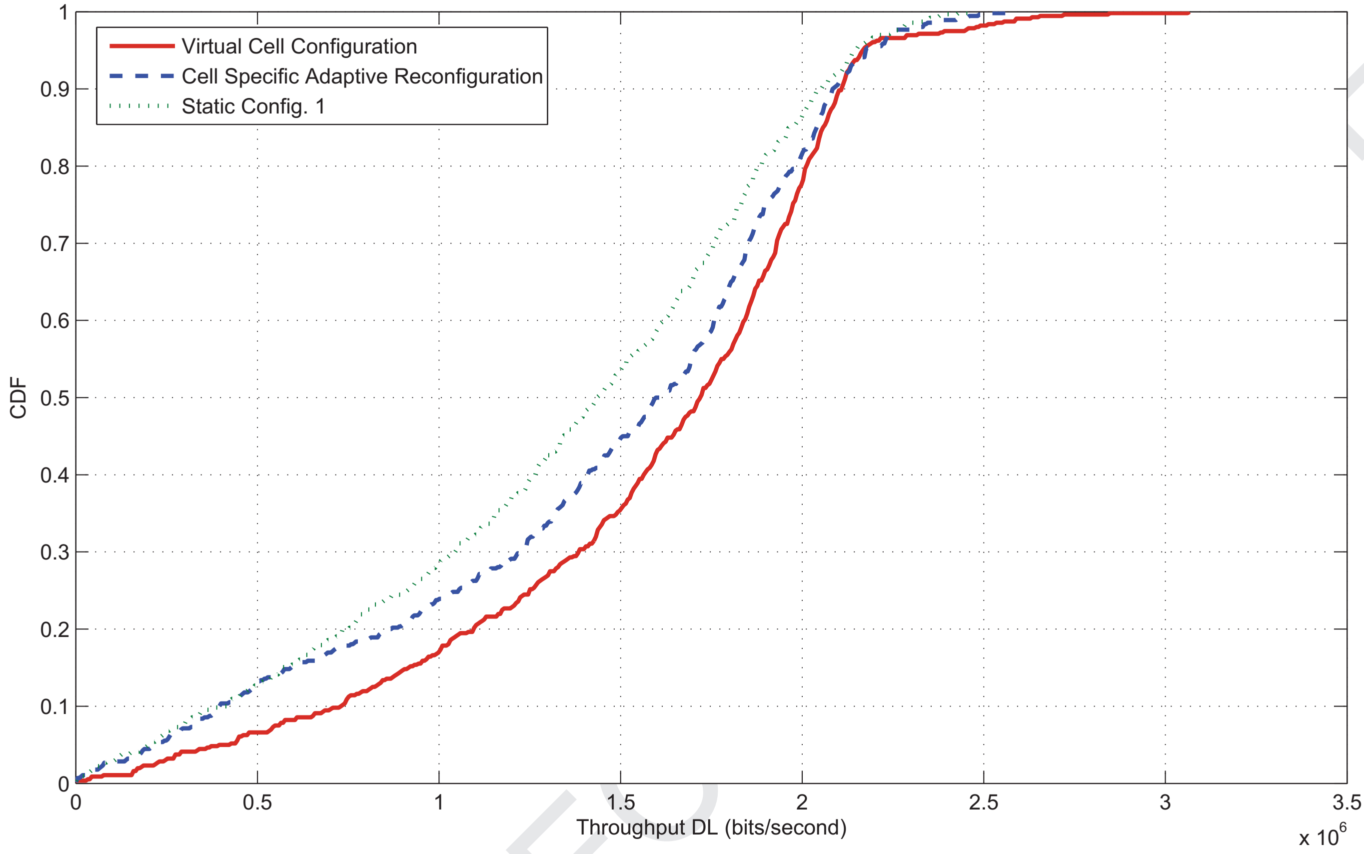

Fig. 3. Downlink Throughput Distribution.

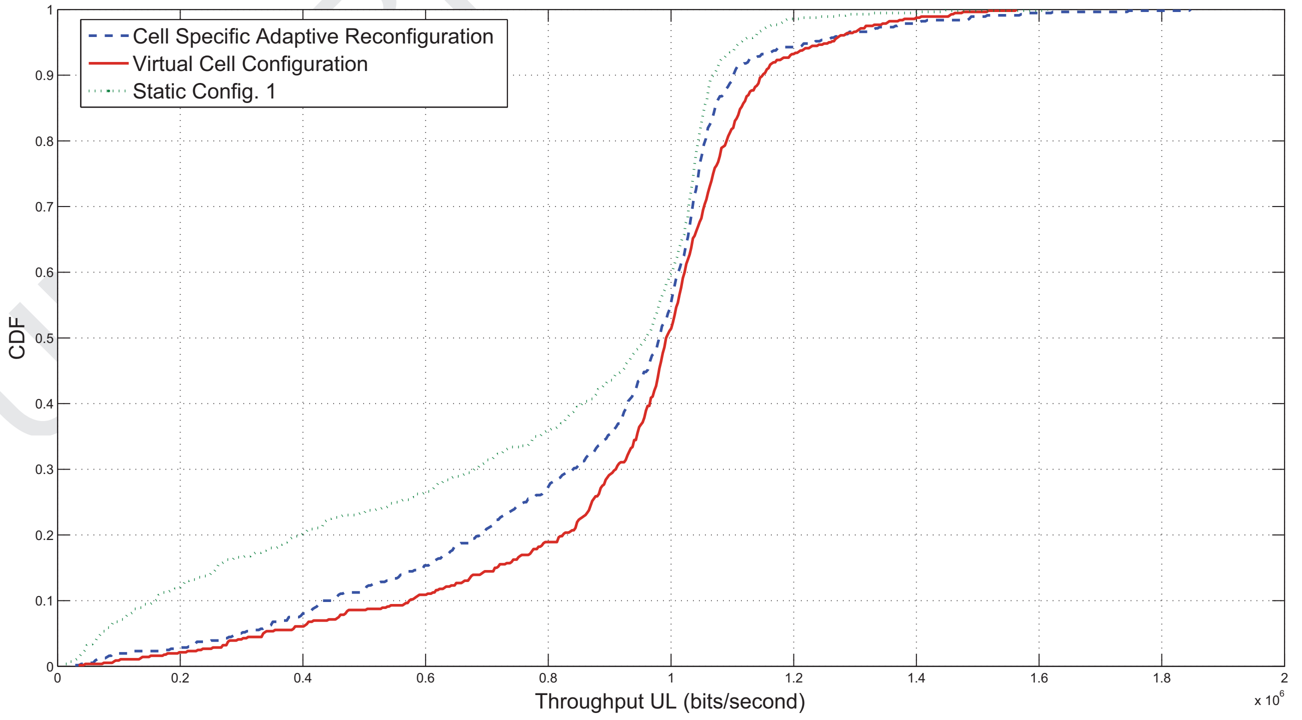

Fig. 4. Uplink Throughput Distribution.

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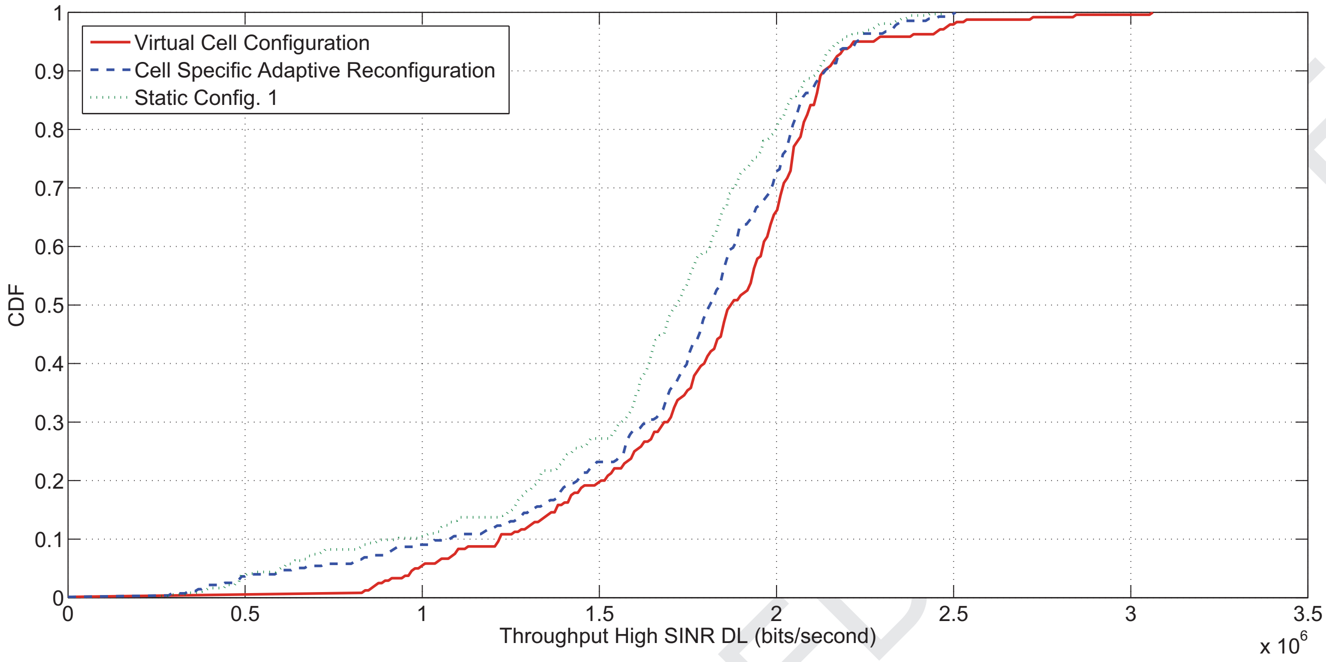

Fig. 5. Throughput Distribution High SINR Inner Cell Users DL.

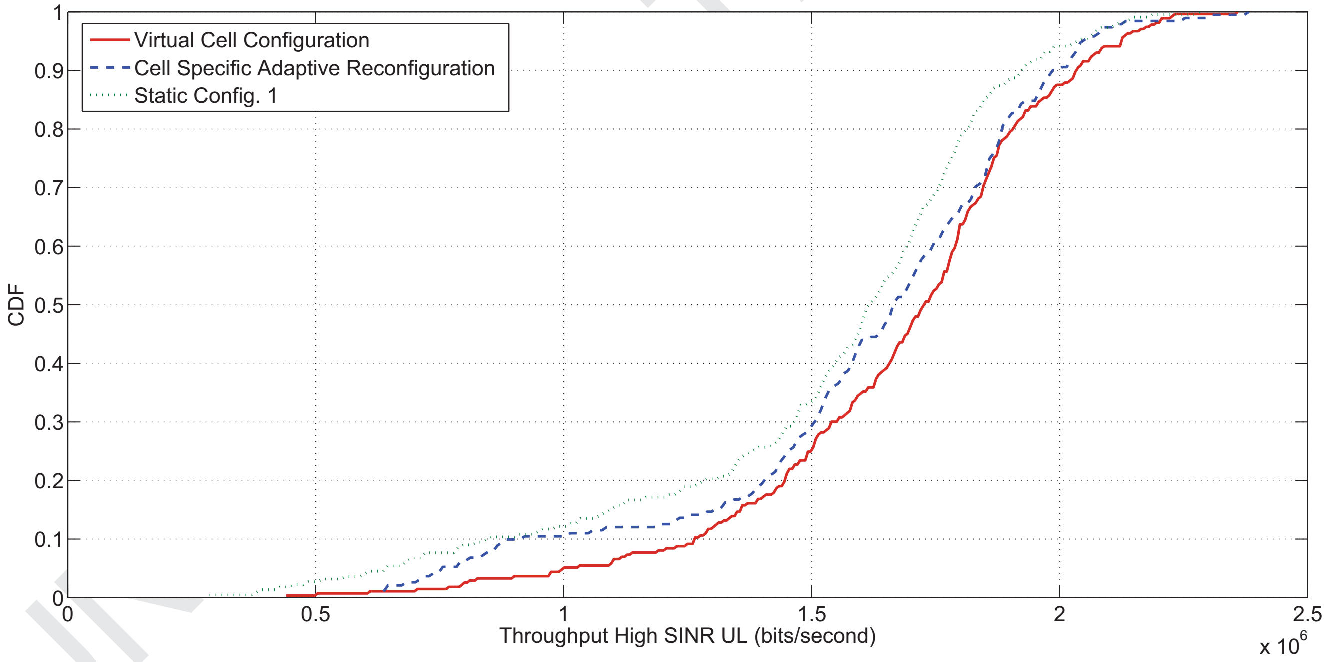

Fig. 6. Throughput Distribution High SINR Inner Cell Users UL.

static UL/DL configuration. For this reason we adopted 3GPP TR 36.828 experimentation scenario and parameters, which are commonly used for driving standards contribution in 3GPP RAN Working Groups. UEs are randomly distributed in the service area and can access the system following a Poisson traffic model, with a mean arrival rate λ. Each UE accessing the system is capable of transmitting a file of size 0.5MB in both UL and/or DL transmission direction at different Transmission Time Intervals (TTIs), assuming that the traffic portion per transmission direction is generated randomly. The system load is controlled by varying the user arrival rate that represents the average number of users accessing the system for transmitting and/or receiving a file. The traffic load of a cell is measured based on the number of active users at a given time and the number of resources used out of the total available resources. The detailed simulation parameters summarized in Table 3 are based-on the 3GPP LTE system specification [28].

We considered a scenario where at any given time, any random cell in the network may experience very high traffic in UL or DL leading to pseudo-congestion, while the other regions in the network carry relatively medium/low traffic. Considering this traffic scenario, we compared the following TD-LTE frame configuration schemes including:

- **Static configuration 1**, where all eNBs employ the same UL/DL configuration, with a subframe ratio of 60% DL and 40% UL.

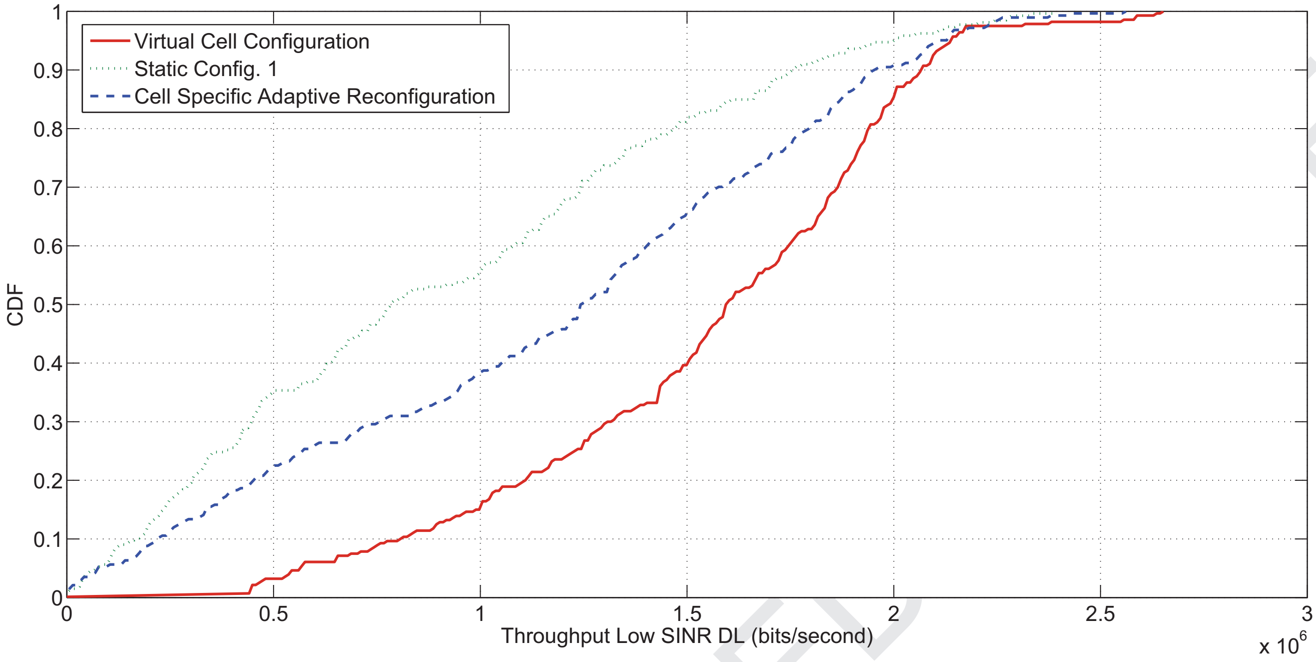

Fig. 7. Throughput Distribution Low SINR Edge Users DL.

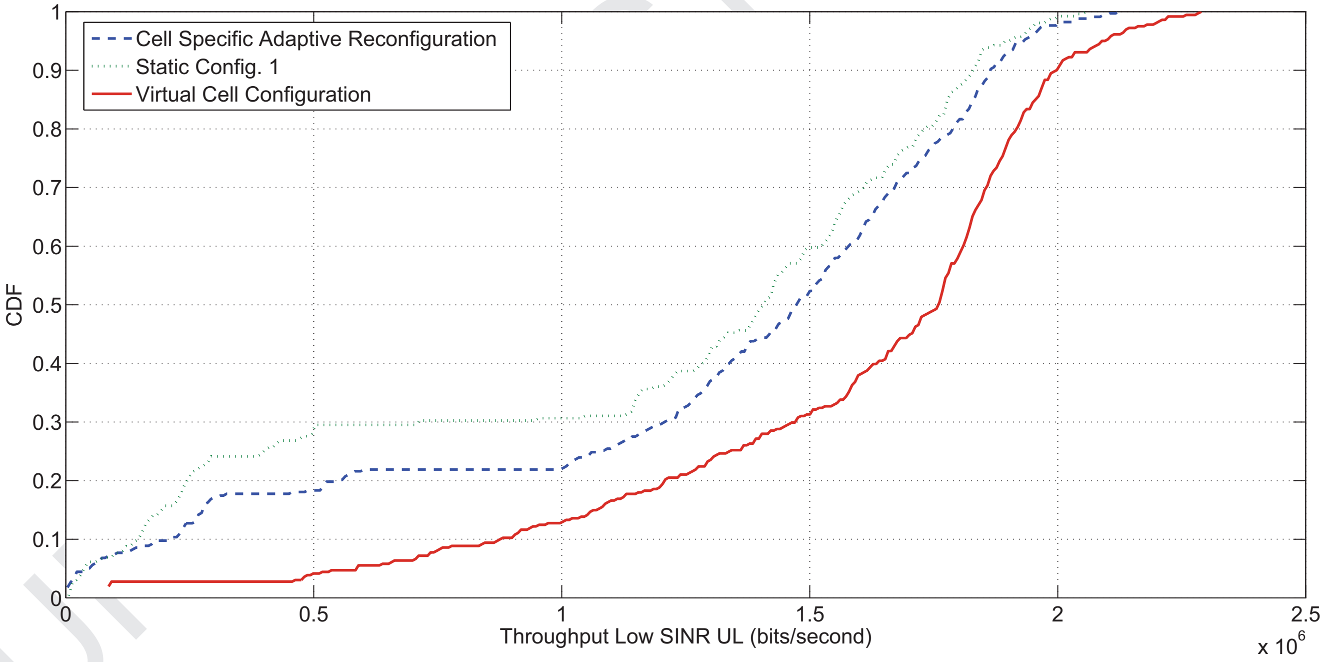

Fig. 8. Throughput Distribution Low SINR Edge Users UL.

- **Cell specific adaptive re-configuration**, where the UL/DL sub-frame ratio is dynamically selected from the set of seven potential TD-LTE frame configurations. The selection of a suitable UL/DL configuration for individual cells is based on estimations of the uplink and downlink traffic demands as detailed in [4].
- **Virtual cell**, that utilizes resources from more than a single cell. Virtual cells are created by the SDN controller, which may optionally enforce an UL/DL re-configuration to a particular cell in order to secure adequate resources for the virtual cell region. Under the virtual cell scheme eNBs can still perform locally a cell specific adaptive re-configuration.

The gain in the throughput performance can be observed in Fig. 3 for DL and Fig. 4 for the UL, which shows the throughput cumulative distribution function (CDF) graphs comparing the three aforementioned configuration schemes. From both figures it is obvious that the Virtual Cell Configuration achieves significant gains in throughput compared to Cell Specific Adaptive Re-configuration and Static Config. 1.

This gain is achieved considering both, the users having low SINR conditions that may reside at the cell edge and the users with relatively higher SINR levels, that may reside in the inner cell and surrounding regions. The throughput of high SINR inner cell users

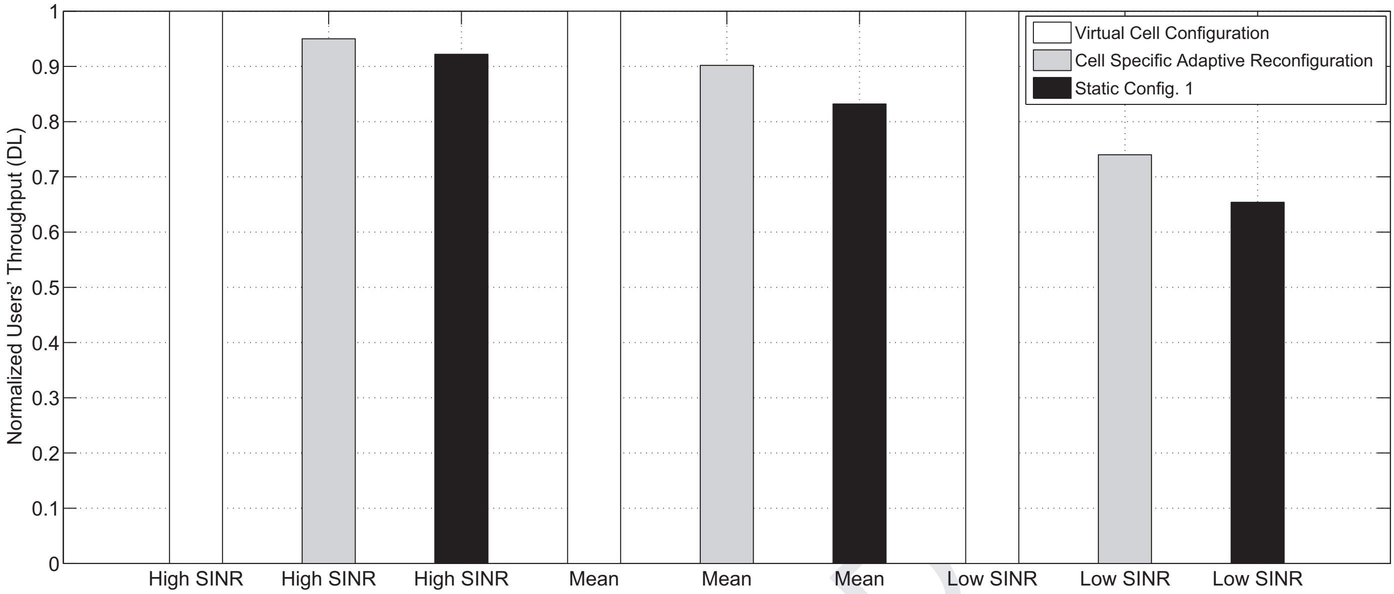

Fig. 9. Downlink Mean and Low SINR Users' Throughput Normalized to the Virtual Cell Configuration.

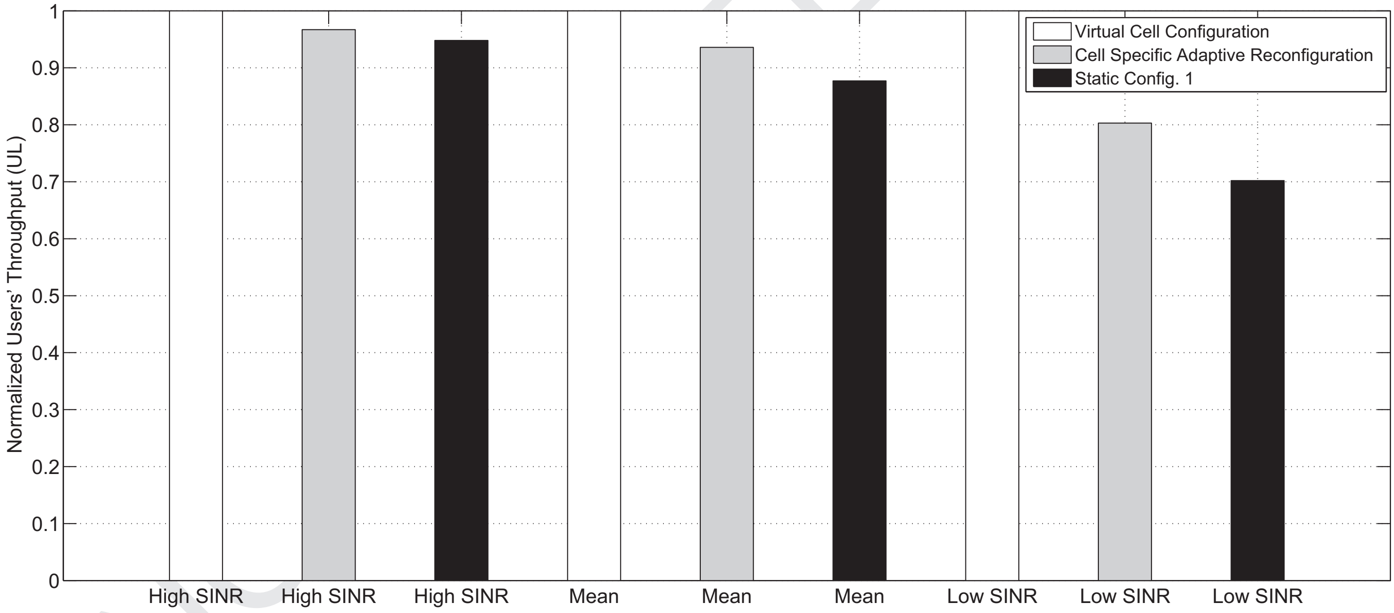

Fig. 10. Uplink Mean and Low SINR Users' Throughput Normalized to the Virtual Cell Configuration.

in DL and UL are presented distinctly in Figs. 5 and 6 respectively. From the figures, it can be observed that high SINR inner cell users do not exhibit loss in throughput for the virtual cells. This clearly indicates that virtual cells have no negative impact on the system performance.

Figs. 7 and 8 show solely the low SINR edge users throughput for DL and UL directions. It can be clearly observed that the virtual cell configuration offers significant gains for the low SINR edge users compare to the Cell Specific Adaptive Re-configuration and Static Config. 1.

The gains offered by the Virtual Cell Configuration are summarized in Figs. 9 and 10, which shows the comparison between the throughput of low SINR edge users, the mean user throughput and the throughput of high SINR inner cell users of the three schemes in DL and UL directions respectively.

The throughput of Cell Specific Adaptive Re-configuration and Static Config. 1 is normalized to the Virtual Cell Configuration which helps in visualizing the gains offered by the Virtual Cell Configuration in comparison with the Cell Specific Adaptive Configuration and Static Config. 1. Clearly, both schemes that provide a flexible UL/DL configuration, i.e. the Cell Specific Adaptive Reconfiguration and Virtual Cell Configuration, result in higher overall throughput, thereby outperforming the Static Config. 1, improving the performance of low SINR users.

In particular, we can observe from Figs. 9 and 10 that the Virtual Cell Configuration provides around 25% improvement in the low SINR user throughput in DL and around 20% in the UL compared to the Cell Specific Adaptive Re-configuration, while 35% and 30% compared to Static Config. 1, in the DL and UL respectively. For the mean user throughput the Virtual Cell Configuration shows an

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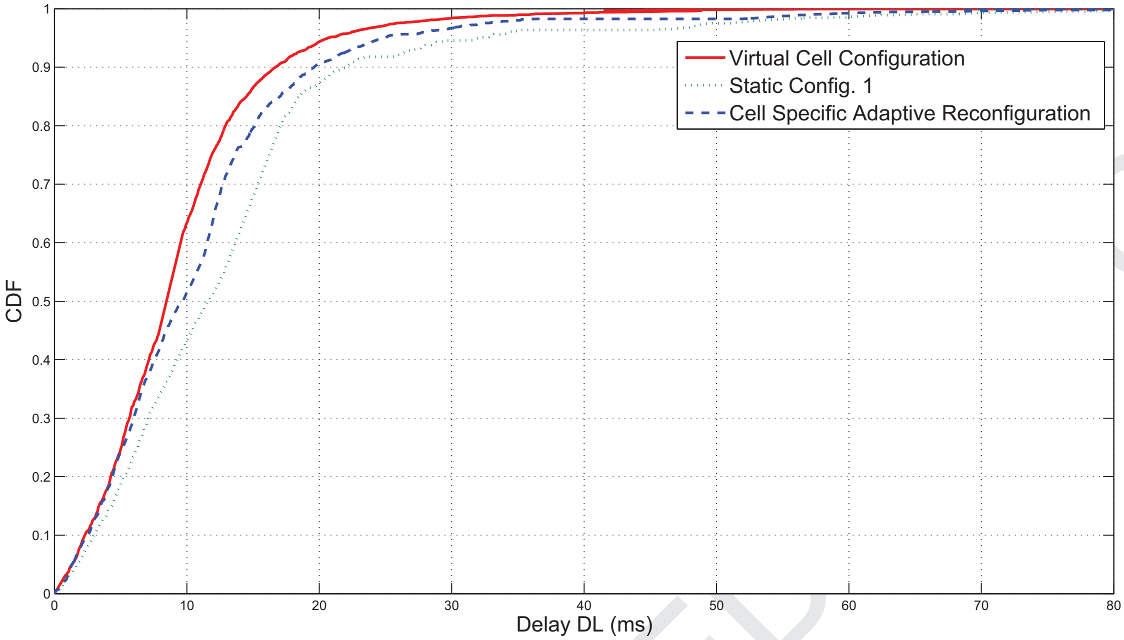

Fig. 11. Downlink Delay CDF.

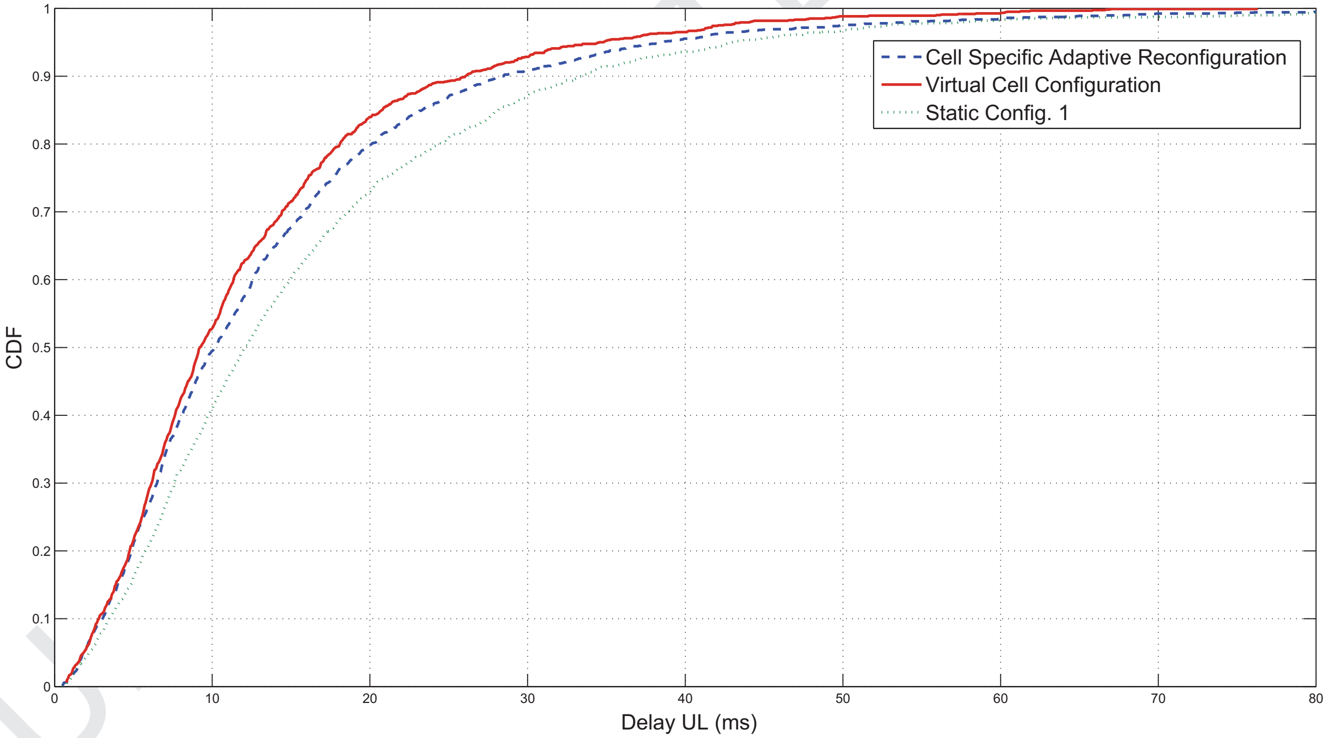

Fig. 12. Uplink Delay CDF.

improvement of 10% in the DL and around 6% in the UL compared to the Cell Specific Adaptive Re-configuration, while around 16% and 12% compared to the Static Config. 1 in DL and UL respectively. The high SINR inner cell users do not experience any negative impact on their performance but instead experience a small gain of 5% and 3% compared to the Cell Specific Adaptive Re-configuration and a gain of around 7% and 6% compared to the Static Config. 1 in DL and UL directions respectively. The reason behind this is due to the fact that some of the low SINR edge users that are served by the virtual cell configuration could free up certain amount of resources that were previously allocated by the serving eNB. These freed up resources can be allocated to the remaining users.

Figs. 11 and 12 illustrate the delay CDFs of the aforementioned three schemes for the DL and UL respectively. It can be observed that the Virtual Cell Configuration achieves significant gains in transmission delay compared to the Cell Specific Adaptive Reconfiguration and Static Config. 1 both for low SINR users, which may reside at the cell edge and other users who experience relatively higher SINR levels, that may reside in the inner cell and surrounding regions.

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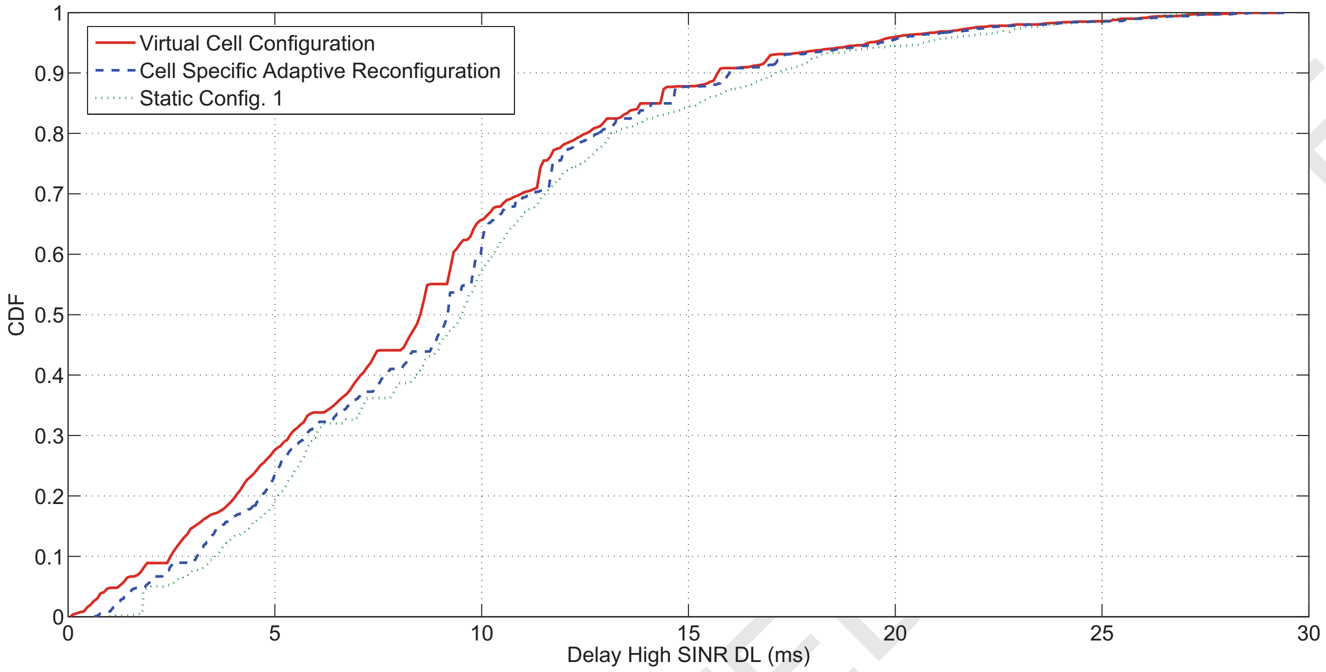

Fig. 13. Downlink High SINR Inner Cell Users' Delay CDF.

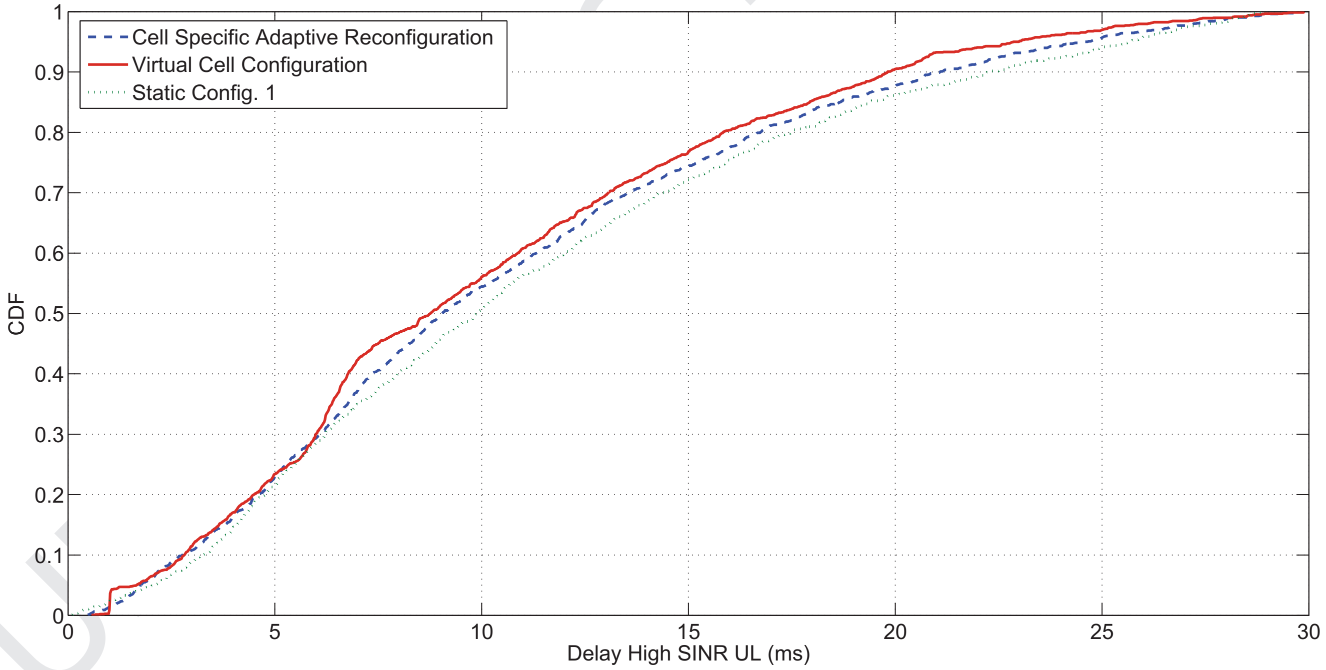

Fig. 14. Uplink High SINR Inner Cell Users' Delay CDF.

The delay of high SINR inner cell users in DL and UL are distinctly presented in Figs. 13 and 14. From the figures, it can be observed that high SINR inner cell users do not experience an increased delay in case of the virtual cell configuration. This confirms that virtual cell configuration has no negative impact on the overall system performance.

Figs. 15 and 16 show the low SINR edge users delay for DL and UL directions. It can be clearly observed that the virtual cell configuration offers significant improvements in terms of delay for the low SINR edge users.

The gains in the transmission delay can also be visualized in Figs. 17 and 18 for the DL and UL direction respectively. As expected, the results are aligned with the throughput gains, as throughput and delay are closely related metrics. To assess the gain in delay offered by the Virtual Cell Configuration, the delay measures of Cell Specific Adaptive Re-configuration and Static Config. 1 are normalized to the delay of the Virtual Cell Configuration. From Figs. 17 and 18 it can be observed that low SINR users in the Virtual Cell Configuration introduce around 25% and 20% less delay than the low SINR users in cell Specific Adaptive Re-configuration,

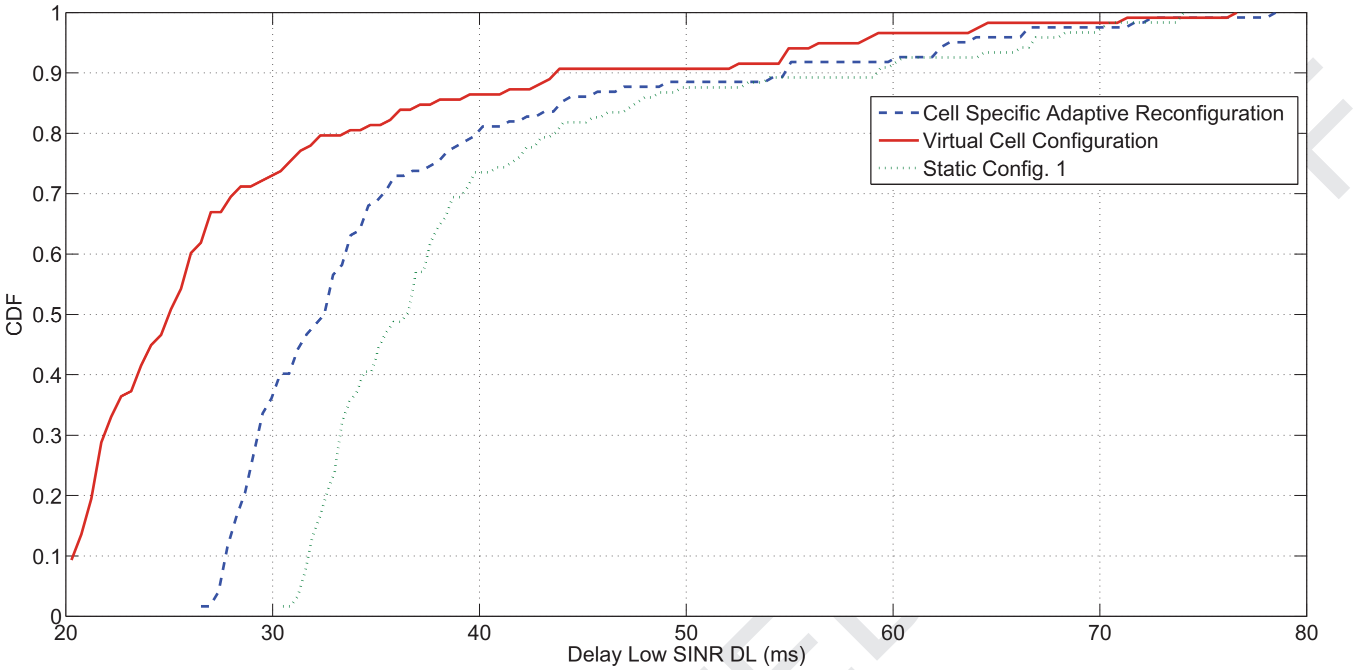

Fig. 15. Downlink Low SINR Inner Cell Users' Delay CDF.

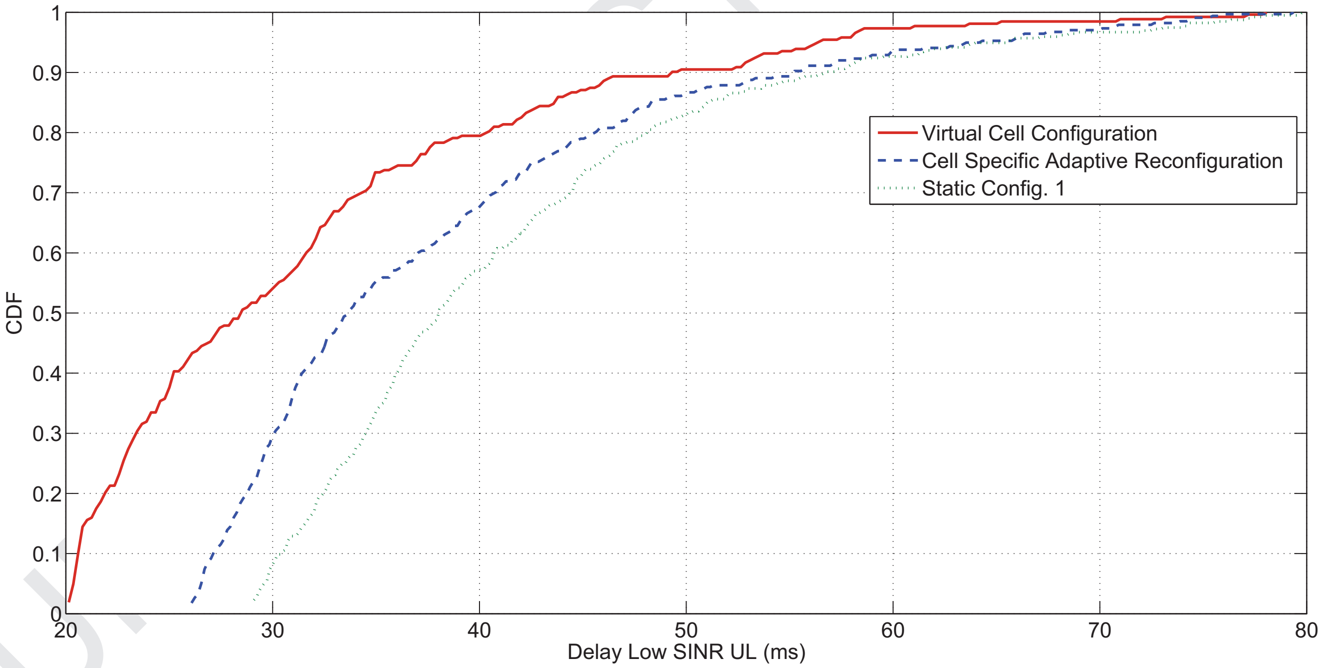

Fig. 16. Uplink Low SINR Inner Cell Users' Delay CDF.

while 35% and 30% compared to the Static Config. 1 in DL and UL respectively.

It is also noted that there is no increase in delay of high SINR inner cell users. In fact a slight reduction in delay of about 5% and 3% is observed compared to the Cell Specific Adaptive Reconfiguration while around 7% and 6% compared to the Static Config. 1 in DL and UL directions. Also, the mean transmission delay for Virtual Cell Configuration is reduced by 10% and 6% in the DL and UL direction compared to the Cell Specific Adaptive Re-configuration and around 16% and 12% compared to the Static Config. 1.

In summary, it is evident from the performance analysis that the Virtual Cell Configuration outperforms the state of the art mechanisms mainly because it can dynamically allocate sub-frames within neighboring cells' overlapping regions for the UL or DL directions according to the real time traffic demands. This provides enhanced flexibility by allowing the system to program the network resources on-demand considering a global network view addressing users' demands at particular cell areas and resolving pseudo congestion.

It is also evident that the users residing in the virtual cell region and served via multiple eNBs could potentially free up

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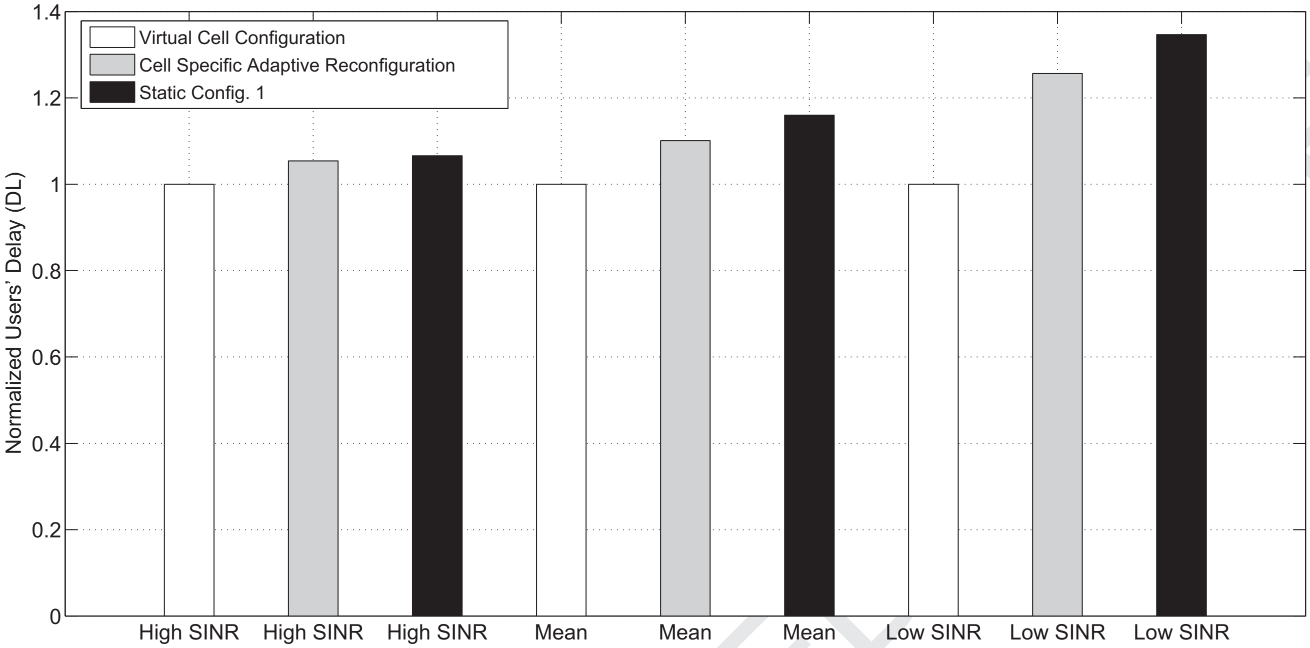

Fig. 17. Downlink Mean and Low SINR Users' Delay Normalized to the Virtual Cell Configuration.

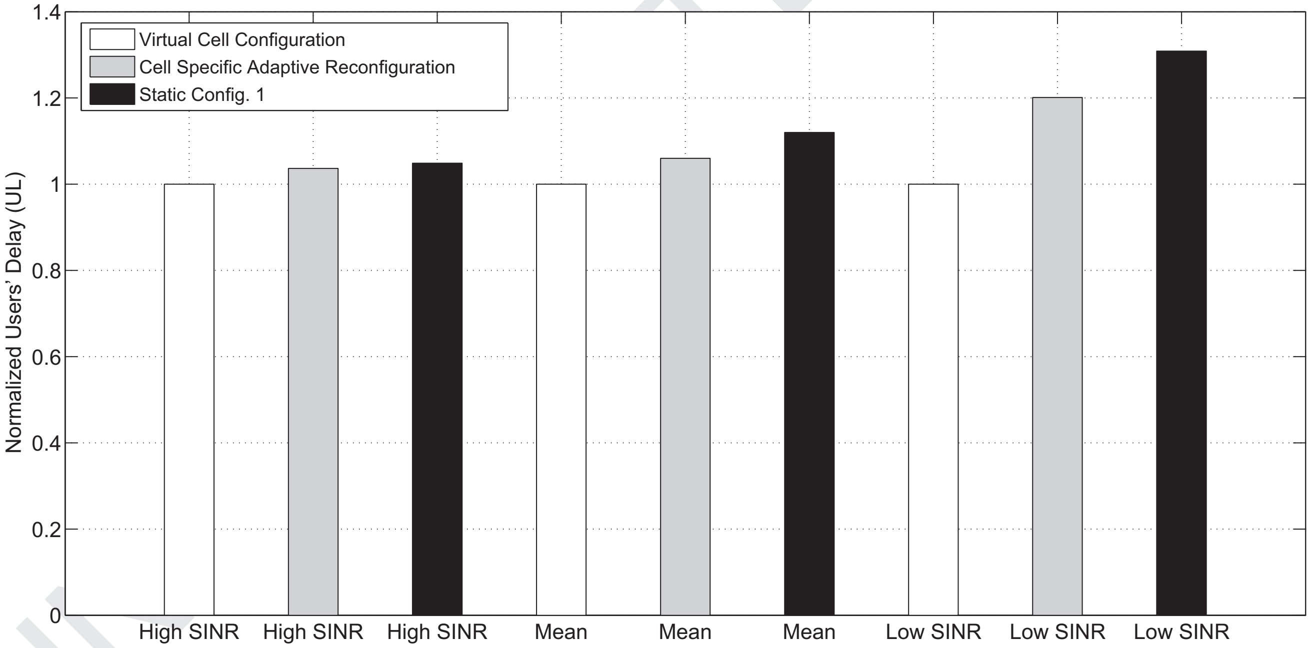

Fig. 18. Uplink Mean and Low SINR Users' Delay Normalized to the Virtual Cell Configuration.

resources for other users in the cell, which may experience enhanced SINR improving the overall network performance.

With the help of SDN based resource management and the use of virtual cells, operators can maintain a tight control over the network with the ability to flexibly allocate resources on-demand, not only to the end users but also to the OTT applications considering the user subscription plans and SLAs. In particular, mobile operators may dynamically program the network to address the traffic needs while considering UL and DL traffic separately, resolving situations that could lead to congestion. In addition, mobile operators can handle efficiently the service elasticity requirements of cloud providers enhancing the quality of experience taking full advantage of the network resource availability.

5. Conclusion

This paper introduced an SDN-based network management architecture and control mechanisms to provide resource elasticity in a TD-LTE system. Such a resource management flexibility introduced by this proposal can enhance the UL/DL diversity in a RAN deployment increasing performance gains, while providing a key enabler for the network operators to support a broad range of OTT application and cloud services with a wide variety of UL/DL traffic demands. The proposed mechanism can address flexibly UL and DL traffic requirements in an autonomous manner addressing effectively pseudo-congestion by forming virtual cells enabling users to utilize resource from multiple eNBs allowing customized frames

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that resolve pseudo-congestion. An algorithm to manage the network resource providing flexibility and enhanced user performance has been introduced at the SDN controller to assess congestion situations and provide resolution via virtual cell provision and by enforcing TD-LTE frame re-configuration at selected eNBs. The results obtained via system level simulations show significant improvements in the average users performance including both edge users that reside within the virtual cell region and inner cell ones, without compromising the overall system performance. Further research is envisioned toward extending the proposed SDN based mechanisms considering split bearers and towards dynamic adjustments in the mobile backhaul provisioning resources for lower layer transport mechanisms.

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