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An Interference Aware Dynamic Spectrum Sharing Algorithm for Local Area LTE-Advanced Networks

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Abstract: -
This paper presents a dynamic spectrum sharing algorithm to minimize the inter-cell interference, so as to achieve a high system performance. This algorithm operates in a self-organized manner without the need of any centralized control, thereby is especially useful in Local Area (LA) where the enhanced-NodeBs (eNB) are close and coordination among them is hard or expensive to achieve. Results show that with very limited signaling between the eNBs, the proposed algorithm can effectively improve the system performance, and it can even overcome the performance with fixed frequency plan.
Keywords: - Interference Awareness, Dynamic Spectrum Sharing, Local Area, LTE-Advanced

I. INTRODUCTION

The International Telecommunications Union – Radio Communication Sector (ITU-R) has recently proposed the new concept of International Mobile Telecommunications – Advanced (IMT-Advanced), which targets to achieve a peak data rate of up to 1Gbps in Local Area (LA) / low mobility [1]. To fulfill this requirement, Long Term Evolution (LTE)-Advanced is proposed, which tries to evolve the current LTE system to meet the IMT-Advanced requirements [2]. With LTE-Advanced, a wide bandwidth of up to 100MHz is expected to be used. This bandwidth should also be best exploited so that the efficiency is as high as possible.

Different from traditional Macro or Micro cells, which cover a wide physical area with potentially a large amount of users, LA has a small coverage and limited number of users. Because of the small cell size of LA networks, the transmission nodes in neighboring cells are not far apart from each other. If their transmissions are not properly coordinated, the receiving nodes will experience very high inter-cell interference. In fact, inter-cell interference is the most important factor that limits the capacity of a LA network. In order to improve the spectral efficiency, the spectrum allocation of neighboring cells should be done in such a way that their mutual interference is minimized. Wireless Local Area Network (WLAN), which is extensively used nowadays, uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CS) to avoid the interference. During our previous study, we have found that CSMA/CA is not efficient in the sense that the back-off window leads to inefficient time slot usage; furthermore, the hidden-nodes problem cannot be properly handled [3]. The Inter-Cell Interference Coordination (ICIC) technique avoids high inter-cell interference by cleverly adjusting the spectrum allocation and transmit power among neighboring cells [4, 5]. Fixed frequency reuse can also be considered as a very simple case of ICIC, where the strongest interference is avoided by using orthogonal frequency bands in neighboring cells. In [6], it is found that fixed frequency reuse with factor 2 achieves much better result than plain reuse 1 in LA scenario. Although efficient, ICIC has its own limitation, which lies mainly in the fact that usually a centralized control element is required to control the transmission parameters. Flexible Spectrum Usage (FSU), as an alternative technique for minimizing inter-cell interference, plays with spectrum allocation [7]. It works in a distributed manner in the absence of any coordination or network planning, thereby suits LA scenario better than ICIC.

The proposed spectrum sharing algorithm in this paper can be classified as a FSU technique. Its performance is evaluated in the context of LTE-Advanced Downlink (DL) transmission. Results show that it achieves much better performance than plain frequency reuse 1 with very limited communication between enhanced-NodeBs (eNBs). In cases when an optimal fixed frequency plan is hard to derive, it can even overcome the performance of any fixed frequency reuse factor.

The rest of the paper is organized as follows: Section II describes in detail the proposed spectrum sharing algorithm. Section III describes the targeted scenarios, simulation methodology and assumptions. Section IV shows the results for the proposed algorithm with different cell layouts, and compared with different frequency reuse factors; in Section V, concluding remarks are given.

II. ALGORITHM DESCRIPTION

The fundamental principle behind the proposed Dynamic Spectrum Sharing with Selfishness (DS^3) is that rather than using all possible spectrum to achieve the highest peak throughput at each moment, one should sacrifice own instantaneous throughput by using less spectrum so as to generate lower interference to others. If everybody follows the same rule, the total network interference can be reduced and the overall performance will increase.

In order to estimate the achievable cell throughput, the modified Shannon's formula is used to approximate the LTE Physical layer performance [8]. With this formula, the capacity in a Single Input Single Output (SISO) system is calculated by:

$$S = \begin{cases} 0 & SINR < SINR_{\min} \\ BW_{eff} \cdot \log_2\left(1 + \dfrac{SINR}{SINR_{eff}}\right) & SINR_{\min} \le SINR \le SINR_{\max} \\ 5.4 & SINR > SINR_{\max} \end{cases} \quad (1)$$

where S is the estimated spectral efficiency in bps/Hz, which is upper limited according to the hard spectral efficiency given by 64QAM with coding rate 9/10; BW_{eff} adjusts for the system bandwidth efficiency of LTE and $SINR_{eff}$ adjusts for the Signal to Noise plus Interference Ratio (SINR) implementation efficiency of LTE. The values for the parameters in Eq. (1) are obtained by extensive link level simulations in macro and micro cell scenarios with 10MHz bandwidth, Turbo coding, 6-taps Typical Urban channel model and LTE frame structure. User velocity is assumed to be 10km/h. Table 1 shows the values for a SISO system.

Table 1. Shannon Curve Fit Parameters for LTE Downlink Link Level Capacity (SISO) [8].

BW_{eff}	$SINR_{eff}$	$SINR_{\min}$	$SINR_{\max}$
0.56	2.0	-10dB	32dB

Following Universal Terrestrial Radio Access Network (UTRAN)-LTE Physical layer structure [9], we divide the whole bandwidth into 500 Physical Resource Blocks (PRB), each PRB is constructed with 12 sub-carriers with sub-carrier spacing of 15kHz. A measurement of Uplink (UL) Received Interference Power (RIP) is also defined in [9]. It is the interference plus thermal noise power measured per PRB at eNB. RIP has been standardized as a measurement that LTE Physical layer should report to higher layers [10]. Although RIP is measured at eNB from UL transmission, we can still use it as a rough indicator for the quality that a user will experience in DL. DS[3] first sorts the PRBs according to RIP, puts the ones with low RIP in the beginning and those with high RIP in the end. Let P, I_k denote the total transmit power at eNB and RIP at the k^{th} PRB respectively, by performing intra-cell resource allocation, e.g. Round Robin (RR) scheduling, this PRB is associated to a user with path gain of g_k, the maximum achievable throughput is then estimated by Eq. (2) as:

$$TP_{\max} = \arg\max_m \left\{ B \cdot \sum_{k=1}^{m} \log_2 \left(1 + \frac{g_k \cdot P/m}{I_k} \cdot \frac{1}{SINR_{eff}} \right) \right\} \quad (2)$$

where $B = 15kHz \cdot 12 \cdot 0.56 = 100.8kHz$ is the effective bandwidth for each PRB; m is the number of PRBs required to achieve the maximum throughput. The PRBs are selected consecutively from the ordered list, starting with the 'best' PRB with lowest RIP.

If the target is to achieve only $X\%$ of the maximum throughput, then only m' PRBs are required. We have $m'/m < X\%$ because the quality for the PRBs is decreasing with PRB index. Fig. 1 gives an example where 86MHz spectrum is required to achieve 100% of the maximum throughput of 120Mbps, while only 49MHz spectrum is needed if the target is to achieve 80% of the maximum throughput, 96Mbps. Note that this figure is obtained at one instance from a DL simulation in a multi-cell LA LTE-Advanced network. Detailed simulation settings can be found in Section III.

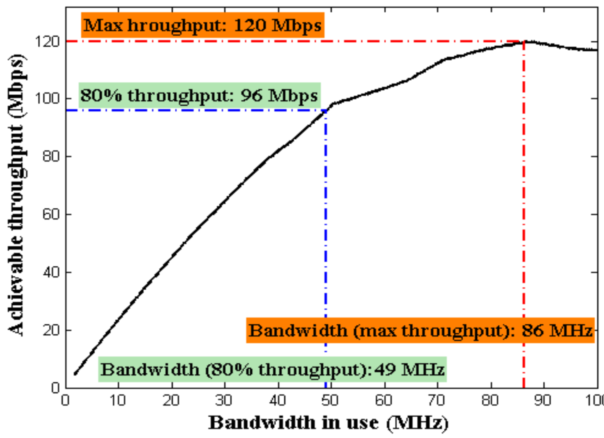

Fig. 1. Basic Idea behind DS[3] Algorithm.

The following flowchart shows what an eNB should do to adopt the DS[3] algorithm and it is described hereafter.

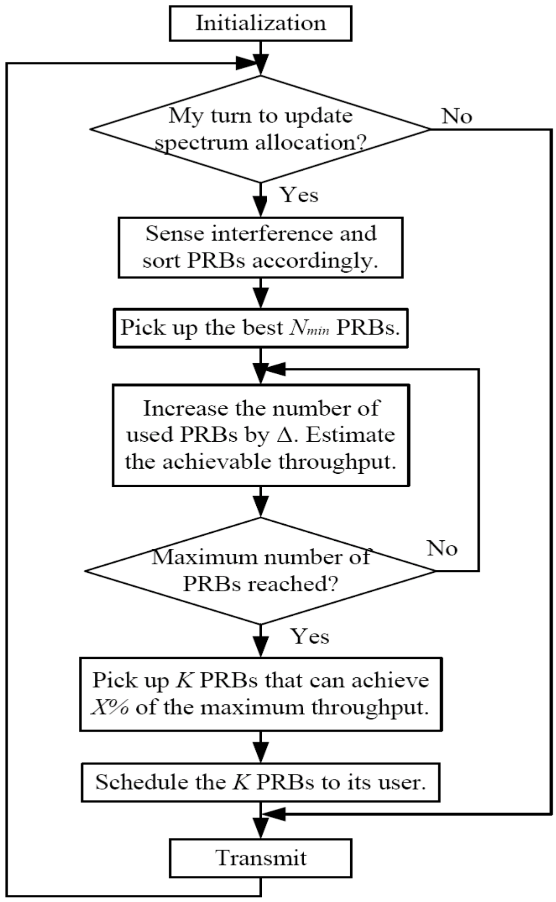

Fig. 2. Flowchart for Using DS[3] in Real Systems.

Step 1: Initialization. In this step, the new eNB will randomly pick up PRBs according to its traffic requirement. Collisions may happen in this phase, and this is dealt within the next steps. During this step, the new eNB should also communicate with existing eNBs and follow a commonly agreed policy to set up a queue for updating the spectrum allocation. This queue contains the identifications of the eNBs and is stored at each eNB for running the algorithm. For instance, the new eNB could be placed in the end of an existing queue. If one eNB switches off, those located after it should shift towards the beginning of the queue by 1. Some signaling overhead will be spent for this purpose. However, this queue remains unchanged unless an eNB enters/leaves the network, which happens in a slow manner. Thereby this overhead is considerably small. Still, if such eNB to eNB links are not available, a random waiting-window can be used to decide on the updating slot and there will be no signaling overhead for setting up the queue. If the time to update the slot has come, go to Step 2. Otherwise, go to Step 7 and transmit with the previous allocation pattern.

Step 2: Sense interference. During this step, the eNB will sense the environment for RIP on each PRB. Afterwards, the eNB sorts them in the order of increasing RIP.

Step 3: With RIP available per PRB, each eNB will select the best $N_{\min}$ PRBs to guarantee their minimum required throughput.

Step 4: Within each iteration, the eNB increases the number of selected PRBs by Δ, which is the incremental granularity, and estimates the achievable throughput using Eq. (2). This step is repeated until the maximum number ($N_{\max}$) of used PRBs is reached. In this step, a PRB with better RIP is always selected before the ones with worse RIP. Note that here the eNB just estimates the achievable throughput; it will select the preferable PRBs based on this estimation in later steps.

Step 5: Find the maximum achievable throughput and pick up K PRBs that can offer $X\%$ of the maximum throughput, as shown in Fig. 1.

Step 6: Schedule/allocate the selected PRBs to the active users.

Step 7: Transmit with the allocation pattern, and wait until its next update slot.

There are a few things worth mentioning:

- The *Selfish Factor* X is used to prevent one cell from taking the whole spectrum. The higher is *X*, the more selfish is a cell. The value of this selfish factor should be carefully chosen according to the average interference level. If inter-cell interference is very high, a small selfish factor should be used, and vice-versa.
- In Step 3, $N_{\min}$ is used to guarantee the basic service. Together with $N_{\max}$ and Δ, they can limit the searching space for DS^3 to tradeoff between complexity and capacity. This is performed in Step 4. For instance, with totally 500 PRBs, if start with 1 PRB until 500, with a granularity of 1 PRB in each iteration, DS^3 requires 500 iterations to finish. However, by setting $[N_{\min}, N_{\max}, \Delta] = [100,400,10]$, only 31 iterations are needed. In cases when the best cell load is roughly known, $N_{\min}$ and $N_{\max}$ can be chosen accordingly so that the optimal point is covered even if the searching space is narrow. Another usage of $N_{\max}$ is to hard limit the maximum spectrum that one cell can get.
- To maintain fairness, the value of X, $N_{\min}$ and $N_{\max}$ should be agreed by all cells as part of a policy. However, different eNBs can have different granularity Δ, depending on their own processing speed.
- By using a queue/waiting-window, we try to make sure that if one eNB is updating its spectrum allocation, its neighbors will follow their old allocation pattern so that the interference condition remains unchanged. Without this queue/waiting-window, if two eNBs are updating at the same time, a collision will happen if they all sense very low RIP for some PRBs and decide to use these PRBs.

III. SCENARIO DESCRIPTION, SIMULATION METHODOLOGY AND ASSUMPTIONS

The indoor LA office scenario described in [11] is used for evaluation of the proposed DS^3 algorithm. It contains 4 eNBs, located at the center of each cell with users randomly distributed within the whole office area. As shown in Fig. 3, each eNB, represented by a gray dot, has an intended coverage area of 50x25m corresponding to 10 office rooms, marked by the same color.

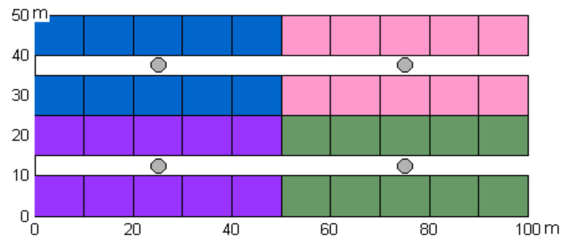

Fig. 3. Office Scenario: eNBs at the Center of Each Cell.

To get a more general view about the performance of the algorithm and its scalability, the extended office scenario with 16 cells is also considered in our studies. With the large amount of simulated cells, it is now easy to evaluate the performance when some of the cells are in idle mode (no users are connected to it). With the dynamic switching on/off of the eNBs, it becomes troublesome to find an optimal frequency plan. Thereby the proposed DS^3 algorithm is expected to be more advantageous than fixed frequency reuse. An example of extended office scenario is shown in Fig. 4, where only active eNBs are shown. Cells with idle eNBs are marked with white color and are crossed out.

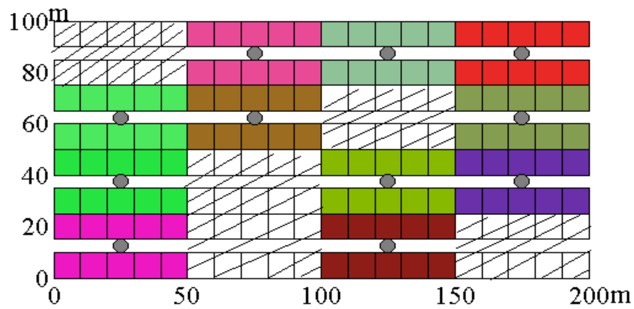

Fig. 4. Extended Office Scenario: both Idle and Active eNBs.

In the simulation, we set $N_{\min}$ equals the number of users to make sure at least one PRB is assigned to a user; $N_{\max}$ equals the total number of PRBs (500) and incremental step Δ=1 PRB, so that all possible PRB allocations are covered. Different values of X are tested to find the best one. The snap-shot based simulation methodology is used for the purpose of evaluating our proposed DS3 algorithm:

1. Within each snap-shot, the cell layout is generated according to the scenario.
2. Users are generated with uniformly distributed locations.
3. The DL SINR is calculated according to the received signal power and interference power level at the user side.
4. The DL throughput is obtained by mapping the calculated SINR according to the ideal link-adaptation based LTE capacity, using Eq. (1).
5. A few thousands of snap-shots are simulated to get the averaged performance.

The following DL performance metrics are used for the evaluation of the system:

1. *Average cell throughput*: this is the cell throughput averaged among all the simulated cells.
2. *Average cell load*: this is the average ratio between average used spectrum and the total spectrum. It tells how much of the total spectrum is used on average by one cell.
3. *Cell edge user throughput*: This is the 5% user outage throughput, which can be obtained as the 5th percentile of the Cumulative Distribution Function (CDF) of user throughput.
4. *Spectrum allocation interval:* This is the time slot that one eNB has to wait before updating its allocation pattern. It is quantified as an integer number of Transmission Time Intervals (TTI).

Fixed DL transmission power is assumed at the eNB. Because our main focus is the spectrum sharing among neighboring cells, we use a simple RR scheduler for the intra-cell spectrum allocation. To further simplify the problem, we do not include the effect of fast fading since its impact is expected to average out over a certain time period.

The assumptions for the simulations in general, including the settings for the link level performance, are according to the LTE specifications [11, 12, 13]. Table 2 gives a short summary.

Table 2. Parameters and Assumptions for System Level Evaluation [11, 12, 13].

PARAMETER	SETTING/DESCRIPTION
Spectrum allocation	100 MHz at 3.5 GHz
Access scheme	DL: OFDMA
Users per cell	5 ~ 10 users
Total transmit power	24dBm
Antenna at eNB	"Omni-directional", 3dBi gain
Antenna at user	"Omni-directional", 0dBi gain
Minimum Coupling Loss	45dB
Receiver noise figure	9dB
Propagation model	
Room size	10x10m
Corridor width	5 m
Internal walls	Light attenuation, 5dB
Path loss model	See [11] for detailed description
Standard deviation of Shadow fading	Line of Sight: 3dB None Line of Sight: 6dB

IV. SIMULATION RESULTS

Performance in Office Scenario with 4 Cells

Fig. 5 shows the DL cell load (the upper plot) and cell throughput (the bottom plot) vs. time in a LTE-Advanced system using DS^3 algorithm. Performance is evaluated with selfish factors of [30%, 50%, 60%, 70%, 80%, 90%].

From this figure it can be seen that a high selfish factor leads to high cell load. However, the best performance is achieved when selfish factor is 80%. The cell load that corresponds to best throughput is around 50%, which is similar to a frequency reuse-2 deployment. It can also be seen that, the DS^3 algorithm converges fairly fast, and a stabilized performance is achieved after 10 update slots.

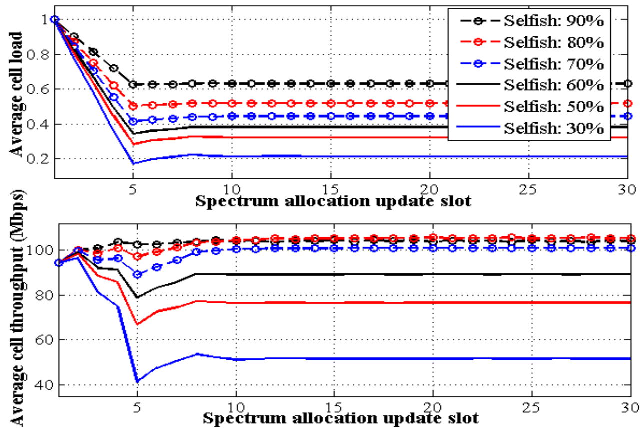

Fig. 5. Time Convergence of DL Cell Load and Average Cell Throughput, with Different Selfish Factors (X).

The performance of the DS^3 algorithm is further compared with the cases using different frequency reuse factors. A selfish factor of 80% is chosen because it offers the best performance. The results are shown in Fig. 6, from which it can be seen that DS^3 achieves much better performance than reuses 1 and 4. When compared to reuse 2, DS^3 is slightly worse in terms of both average cell throughput and cell edge throughput. However, as can be seen from the right side of the figure, when interference is low, DS^3 offers the possibility to use nearly the whole spectrum and achieve much better performance than reuse 2. Most importantly, frequency reuse requires a careful network planning while our proposed DS^3 algorithm works in a self-organized manner. This makes it a much better solution compared to simple fixed frequency reuse in LA networks.

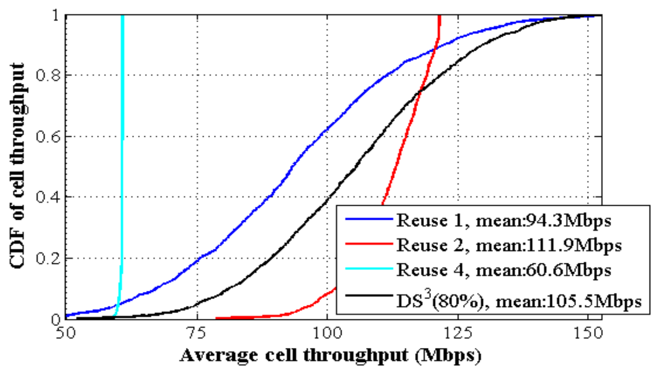

Fig. 6. CDF of DL Average Cell Throughput: DS^3 Compared with Fixed Frequency Reuse

Performance in Extended Office Scenario with 16 Cells

The performance when 20% and 50% of the eNBs are in idle mode is shown in Fig. 7 and Fig. 8. From which it can be seen that:

- DS^3 with selfish factor of 70% achieves always the highest cell edge user throughput, which is around 150% higher than frequency reuse 1, and 50% higher than reuse 2.
- In terms of average cell throughput, DS^3 with selfish factor 70% achieves slightly worse performance than frequency reuse 1, but similar as reuse 2 and much better than reuse 4. By tuning the selfish factor, a high average cell throughput can be achieved at the cost of a reduced cell edge user throughput.
- Based on the simulation result, DS^3 with selfish factor 70% seems to be the best trade-off between the two throughput metrics selected in this study.

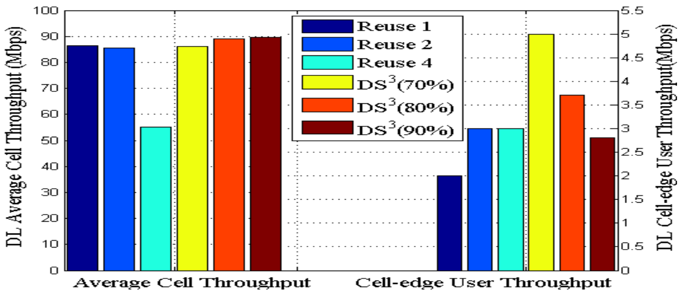

Fig. 7. Fixed Frequency Reuse vs. DS^3 in Extended Indoor Office Scenario, with 20% Idle eNBs.

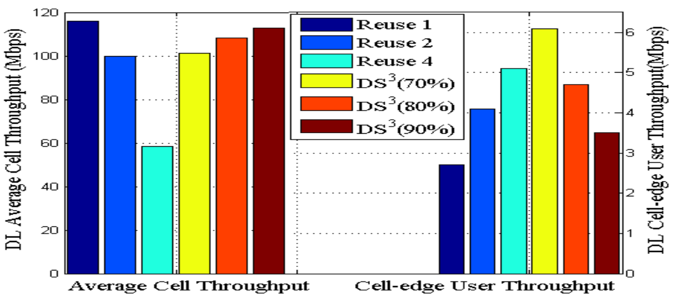

Fig. 8. Fixed Frequency Reuse vs. DS^3 in Extended Indoor Office Scenario, with 50% Idle eNBs.

V. CONCLUSION

In this paper, we proposed an interference aware dynamic spectrum sharing algorithm, Dynamic Spectrum Sharing with Selfishness (DS^3), in the context of LTE-Advanced. It dynamically minimizes the inter-cell interference and significantly improves the system performance. The DS^3 algorithm requires very limited signaling between eNBs to set up an update queue for initialization. After that, the algorithm runs in a distributed manner and requires no more signaling. It uses UL RIP, which is available in current LTE systems, as a rough channel quality indicator. These features make the proposed algorithm mostly suitable for LA scenarios, where the optimal frequency plan is hard and costly to achieve, because of the lack of a centralized control element or eNB to eNB communication. The novelty of the proposed algorithm lies in the 'selfish' factor, which prioritizes the overall throughput rather than the individual performance per cell. The performance of the proposed DS^3 algorithm is evaluated and compared against fixed frequency reuse schemes. Despite of the operation simplicity, DS^3 provides similar or even better performance than fixed frequency reuse.

There are some possibilities to further improve the performance of DS^3: firstly, if the users are able to sense the whole spectrum and report back their interference condition, the eNB will have a better and more accurate estimation about the achievable throughput. This in turn, should provide a better spectrum allocation than using UL RIP. However, this comes with high complexity at the user side and high feedback overhead. Secondly, as can be seen from the results, the performance of DS^3 is very sensitive to the fairness factor. Constant values are used in this study. To make this algorithm fully self-organized, a way to automatically find out the best selfish factor has to be developed. Lastly, each eNB updates its spectrum allocation periodically using a simple timer. It may be beneficial to consider the traffic requirement from the users or the request from neighboring cells as the trigger to update spectrum allocation.

In this paper we show only the DL results with fixed eNB location. Similar results were obtained for UL and also in the case where eNBs are randomly located within a network. Although TDD is assumed as the duplexing scheme in this study, the conclusions and observations are in general valid also for FDD systems, because the UL RIP measurement is available in both systems.

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