Dynamic TDD Transmissions in Homogeneous Small Cell Networks

Ming Ding[1], David López Pérez[2], Athanasios V. Vasilakos[3] and Wen Chen[4]
1) Sharp Laboratories of China, P. R. China {ming.ding2012@gmail.com}
2) Bell Laboratories Alcatel-Lucent, Ireland {dr.david.lopez@ieee.org}
3) Kuwait University, Kuwait {th.vasilakos@gmail.com}
4) Shanghai Jiao Tong University, P. R. China {wenchen@sjtu.edu.cn}

***Abstract*—In this paper, we investigate the performance of dynamic time division duplexing (TDD) transmissions with various kinds of interference management strategies, i.e., cell clustering (CC), power control and interference cancellation (IC), as well as their combinations in homogeneous small cell networks. We present extensive results on network performance in terms of downlink (DL)/uplink (UL) wide-band (WB) signal-to-interference-plus-noise ratio (SINR), 95-, 50- and 5-percentile user equipment (UE) packet throughputs (UPTs). We also study the impact of high-order modulation schemes on dynamic TDD. Our work shows that, when the traffic load is low to medium, an advanced dynamic TDD scheme with UL power boosting (ULPB), IC and full flexibility of TDD configuration is shown to immensely outperform the static TDD scheme by approximately 30~60 % and 210~300 % in terms of the DL and the UL UPTs, respectively.**

I. Introduction

Currently, the Third Generation Partnership Project (3GPP) sees exciting activities in the design of Long Term Evolution (LTE) Release 12 networks [1], in which the small cell enhancement (SCE) study item has a lot of momentum. Future small cell networks are envisaged to prioritize time division duplexing (TDD) schemes over frequency division duplexing (FDD) schemes because TDD transmissions are more suitable for hot spot scenarios with traffic fluctuations in both link directions [2]. In the 3GPP LTE Release 8~11 networks, seven TDD configurations [3], each associated with a downlink (DL)/ uplink (UL) subframe ratio in a 10-millisecond transmission frame, are available for semi-static selection at the network side. However, this semi-static selection is not able to adapt DL/UL subframe resources to the fast fluctuation in traffic load generated at the small cells due to the low number of connected UEs and the burstiness of their DL/UL traffic.

In order to allow small cells to smartly adapt their communication service to the quick variation of DL/UL traffic demands, a new technology, referred to as dynamic TDD, has drawn much attention. In dynamic TDD, the TDD configuration can be dynamically changed in each or a cluster of cells. Dynamic TDD can thus provide a tailored configuration of DL/UL subframe resources at the expense of allowing inter-link interference, i.e., DL-to-UL and UL-to-DL interference. The application of basic dynamic TDD transmissions in homogeneous small cell networks has been investigated in recent works [4]. Gains in terms of wide-band (WB) signal-to-interference-plus-noise ratio (SINR) and user equipment (UE) packet throughput (UPT) have been observed, mostly in low-to-medium traffic load conditions.

In this paper, we present new results on dynamic TDD transmissions in homogeneous small cell networks. In particular, we investigate dynamic TDD schemes with various kinds of interference management strategies and present results on network performance in terms of WB SINR, 95-, 50- and 5-percentile UPTs. The contribution of this paper is two-fold:

1) The effectiveness of various inter-link interference management schemes, such as cell clustering (CC) [2], power control [5], [6], interference cancellation (IC), as well as their combinations, is systematically investigated and compared.
2) The impact of high-order modulation schemes on dynamic TDD is studied.

The rest of the paper is organized as follows: Sections II, III, and IV present the network scenario, a formal description on the dynamic TDD DL/UL subframe splitting, and the interference mitigation schemes evaluated in this work, respectively. Section V provides our new results on dynamic TDD, followed by some concluding remarks in Section VI.

II. Network Scenario

During the study item phase of dynamic TDD in the 3GPP, a total of eight deployment scenarios were considered for investigation [2]. After preliminary assessment of technical feasibility and performance evaluation, the following two scenarios were prioritized for further study [1]:

- Scenario 3: Multiple outdoor picocells deployed on the same carrier frequency.
- Scenario 4: Multiple outdoor picocells deployed on the same carrier frequency, and multiple macrocells deployed on an adjacent carrier frequency, where dynamic TDD schemes can only be used in small cells.

Fig. 1 illustrates Scenarios 3 and 4. In Fig. 1, the n-th small cell base station (BS) and the k-th UE are denoted as $c(n), n \in \{1, \ldots, N\}$ and $u(k), k \in \{1, \ldots, K\}$, respectively. The UE's reference signal received power (RSRP) associated with small cell BS $c(n)$ is denoted as $RSRP_{n,k}$.

978-1-4799-4640-2/14/$31.00 ©2014 IEEE

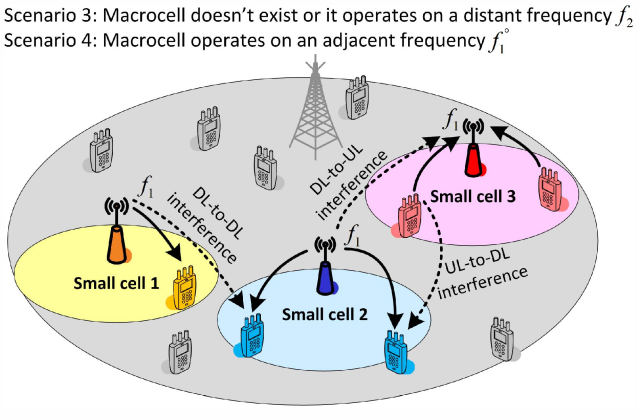


Figure 1. Illustration of Scenarios 3 and 4 of dynamic TDD

Based on the best RSRP criterion for small cells, the set of small cell UEs served by small cell BS $c(n)$ is denoted by $U_{(n)} = \left\{u(q_{n,1}), \dots, u(q_{n,k}), \dots, u\left(q_{n,K(n)}\right)\right\}$, where $Q_{(n)} = \left\{q_{n,1}, \dots, q_{n,k}, \dots, q_{n,K(n)}\right\}$ is the set of indices of such small cell UEs and $K(n)$ is its cardinality. The DL and the UL traffic arriving rates, the DL and the UL data buffers of small cell UE $u(q_{n,k})$ are respectively denoted as $\lambda^{\mathrm{DL}}(q_{n,k})$, $\lambda^{\mathrm{UL}}(q_{n,k})$, $\omega^{\mathrm{DL}}(q_{n,k})$ and $\omega^{\mathrm{UL}}(q_{n,k})$.

III. Dynamic DL/UL Subframe Splitting

In this section, we present an algorithm that runs independently in each small cell and decides whether a DL or an UL subframe should be scheduled in a given dynamic TDD subframe. The optimization objective is to minimize the difference between the DL and the UL instantaneous traffic demand densities in each small cell (seeking balanced DL/UL performance). Here, the instantaneous traffic demand density is defined as the sum of UEs' instantaneous DL/UL data buffers over the quantity of the corresponding subframe resources in T subframes. The instantaneous traffic demand density of small cell $c(n)$ in the DL is defined as

$$\tilde{d}_n^{\mathrm{DL}}(t) = \frac{\sum_{k \in Q_{(n)}} \omega^{\mathrm{DL}}(q_{n,k})}{t}, \qquad (1)$$

wherein the numerator is the sum of instantaneous DL data buffers $\omega^{\mathrm{DL}}(q_{n,k})$ of all UEs $k \in Q_{(n)}$ connected to small cell $c(n)$, and the denominator is the number of available DL subframes in T subframes denoted as t. Similarly, the instantaneous traffic demand density of small cell $c(n)$ in the UL can be defined as

$$\tilde{d}_n^{\mathrm{UL}}(t) = \frac{\sum_{k \in Q_{(n)}} \omega^{\mathrm{UL}}(q_{n,k})}{T - t}. \qquad (2)$$

Then, with respect to minimize the difference between the DL and the UL instantaneous traffic demand densities, the optimal number of dynamic TDD DL subframes in T subframes for small cell $c(n)$ is selected from

$$t_n^{\mathrm{INST}} = \arg\min_{r \in \Upsilon} \left\{ \left| \tilde{d}_n^{\mathrm{DL}}(g(r)) - \tilde{d}_n^{\mathrm{UL}}(g(r)) \right| \right\}, \qquad (3)$$

where Υ is the set of all available TDD configurations, r is one specific TDD configuration, and $g(r)$ extracts the number of DL subframes in T subframes from the TDD configuration r. Note that $g(r)$ may not be limited to integer values since in practical systems certain special subframes consist of DL symbols, UL symbols and a transition interval between the DL and the UL symbols. The proportion of these three parts depends on the specific TDD configuration r.

In addition, when a small cell $c(n)$ is completely idle, i.e., $\forall \omega^{\mathrm{DL}}(q_{n,k}) = 0$ and $\forall \omega^{\mathrm{UL}}(q_{n,k}) = 0$, $k \in Q_{(n)}$, we propose that the number of dynamic DL subframes should be set to a statistically optimal value that matches the upcoming traffic, which can be characterized by UEs' average traffic arriving rates $\lambda^{\mathrm{DL}}(q_{n,k})$ and $\lambda^{\mathrm{UL}}(q_{n,k})$. Similar to $\tilde{d}_n^{\mathrm{DL}}(t)$ and $\tilde{d}_n^{\mathrm{UL}}(t)$, we define the average DL and UL traffic demand densities in small cell $c(n)$ as $d_n^{\mathrm{DL}}(t) = \frac{\sum_{k \in Q_{(n)}} \lambda^{\mathrm{DL}}(q_{n,k})}{t}$ and $d_n^{\mathrm{UL}}(t) = \frac{\sum_{k \in Q_{(n)}} \lambda^{\mathrm{UL}}(q_{n,k})}{T-t}$. We then propose that in the respect of minimizing the difference between the DL and the UL average traffic demand densities, the statistically optimal number of dynamic TDD DL subframes for small cell $c(n)$ is selected from

$$t_n^{\mathrm{STAT}} = \arg\min_{r \in \Upsilon} \left\{ \left| d_n^{\mathrm{DL}}(g(r)) - d_n^{\mathrm{UL}}(g(r)) \right| \right\}. \qquad (4)$$

IV. Interference Mitigation Schemes

It can be expected that the dynamic TDD DL/UL subframe splitting described in Section III enables traffic-adaptive scheduling, i.e., more UL subframes will be diverted to DL transmissions when the DL traffic demand density in a small cell is higher than the UL one and vice versa. However, dynamic TDD DL/UL subframe splitting gives rise to a new type of interference, which is the inter-link interference between DL and UL transmissions resulted from non-uniform TDD subframe configurations among adjacent cells. Such kind of interference is particularly severe in the DL-to-UL case because the high-power DL signal from a BS may easily overwhelm a UE's low-power UL signal intended for another BS. Various inter-link interference mitigation (ILIM) schemes can be applied to address this DL-to-UL interference problem, such as cell clustering (CC) [2], DL power reduction (DLPR) [5], UL power boosting (ULPB) [6], interference cancellation (IC), as well as their combinations. In the following, we present these techniques, which will be compared in later sections.

A. Cell clustering

The CC scheme organizes the small cells in the network into cell clusters based on metrics such as coupling loss PL^{CC}, i.e., the path loss between small cell BSs [2]. Then, the dynamic TDD configuration is conducted on a per-cell-cluster basis, rather than on a per-cell basis. In other words, the TDD configuration of all the small cells in a cell cluster is the same, thus inter-link interference is eliminated within such cell cluster. In this case, negotiation and coordination of TDD configurations within cell clusters are required through inter-cell communications over backhaul links or the air interface. A simple method to perform dynamic TDD DL/UL subframe splitting for cell clusters is to sum $\tilde{d}_n^{\mathrm{DL}}(t)$ and $\tilde{d}_n^{\mathrm{UL}}(t)$, as well as $d_n^{\mathrm{DL}}(t)$ and $d_n^{\mathrm{UL}}(t)$ over the small cells in the same cell cluster and proceed accordingly with the algorithm described in Section III.

B. Power Control

The power control strategy includes the DLPR [5] and ULPB schemes [6]. The DLPR scheme sacrifices DL performance in exchange of decreasing the DL-to-UL interference and thus improving the UL performance. In contrast, the ULPB scheme allows more transmit power consumption at the UE side to combat the DL-to-UL interference coming from small cells. The implementation of the power control techniques is relatively simple, i.e., a fixed power offset ΔP^{DL} and ΔP^{UL} can be configured on top of the DL and UL power level, respectively.

C. Interference Cancellation

In this paper, the IC scheme refers to the DL-to-UL IC because it is technically feasible to assume that small cell BSs are capable of cancelling interference coming from neighboring BSs. In contrast, the assumption of UEs performing UL-to-DL IC with regard to other peer UEs would seem to be too farfetched and impractical. The IC scheme provides the best ILIM for the UL, but requires good backhaul connections for inter-cell information exchange on DL transmission assumptions, including resource allocation, modulation and coding scheme (MCS), configuration of demodulation reference signals, etc. Besides, strong signal processing modules in small cell BSs are needed to detect, reconstruct and cancel the DL interference from UL signals.

V. SIMULATIONS AND DISCUSSIONS

In this section, we conduct system-level simulations and present numerical results to compare the performance of the existing static TDD scheme in LTE Release 11 with that of dynamic TDD transmissions in LTE Release 12 and an enhanced version with full flexibility of dynamic TDD configuration, which probably falls into the scope of LTE Release 13. We also consider the ILIM techniques presented in Section IV and their combinations, and investigate the performance gains of dynamic TDD with basic and combined ILIM schemes.

We concentrate our analysis on the 3GPP dynamic TDD Scenario 3, i.e., a homogeneous layer of outdoor picocells as illustrated in Fig. 1. The full list of system parameters and the traffic modeling methodology can be found in [2] and [7], respectively. More information on the system-level simulator used for this analysis can be found in http://wnt.sjtu.edu.cn/flint/html/index.html. Some key parameters adopted in our simulations are presented in Table I. The traffic model is assumed to be Poisson distributed with $\lambda^{\mathrm{DL}}(q_{n,k})$ taking a uniform value for all UEs. The values of $\lambda^{\mathrm{DL}}(q_{n,k})$ are {0.05, 0.15, 0.25, 0.45} packets per UE per second. Besides, we assume $\lambda^{\mathrm{UL}}(q_{n,k}) = 0.5 \times \lambda^{\mathrm{DL}}(q_{n,k})$, as recommended in [2]. The packet size is fixed to be 0.5 Mbytes. Packets are independently generated for the DL and the UL in each small cell, and they are randomly assigned to small cell UEs. Additionally, we assume that $T = 10$. Note that in our simulations we adopt the common assumption in the 3GPP that UE is equipped with 1 antenna for transmission and 2 antennas for reception (see Table I).

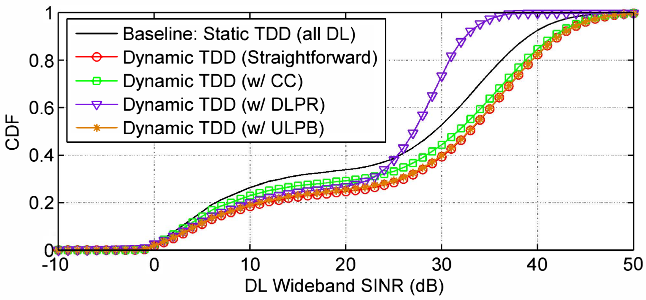
Table I
KEY SIMULATION PARAMETERS

Parameters	Assumptions
Cellular model and layout	7 cell sites, 3 cells per cell site
Inter-site distance	500 m
# picocells per cell	4, radius of coverage: 40 m
# UEs per picocell	10, uniformly dropped
System bandwidth	10 MHz
# picocell antenna	4 for both Tx and Rx [3]
# UE antenna	1 for Tx, 2 for Rx [2]
UE scheduling in each cell	Proportional fairness (PF)
Packet scheduling for UE	Round Robin (RR)
MC schemes	QPSK, 16/64/256QAM [1]
Non-data overhead	3 OFDM symbols per subframe
Small-scale fading channel	EPA channel model defined in [8]
Receiver type	MMSE receiver [2]

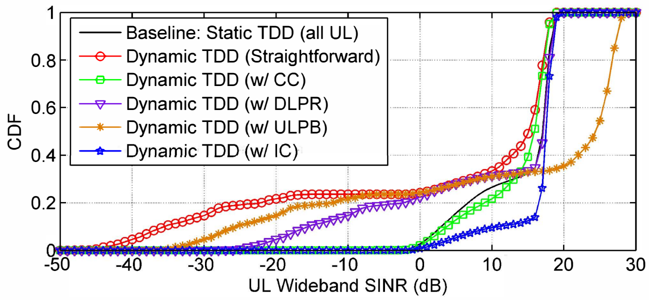
A. Performance of DL/UL WB SINR

First, we check the performance of DL/UL WB SINR to get some overall ideas about how dynamic TDD with or without ILIM affects the link-level performance. For the CC scheme, the coupling loss threshold PL^{CC} for small cells within a cell cluster is set to 90 dB [2]. For the DLPR and the ULPB schemes, ΔP^{DL} and ΔP^{UL} are set to -20 dB and 10 dB, respectively. For the IC scheme, since we only consider the DL-to-UL IC, its impact on the DL WB SINR is none, thus we evaluate the IC scheme only for the UL. Besides, since $\lambda^{\mathrm{DL}}(q_{n,k}) : \lambda^{\mathrm{UL}}(q_{n,k}) = 2 : 1$, we assume that in dynamic TDD the probability of observed DL subframes and that of UL ones are 2/3 and 1/3, respectively. Furthermore, we drop the assumption of full-buffer traffic load as in the existing works [2], [4], and instead we consider a more practical network scenario with the probability of the occurrence of interference being 0.4. The cumulative density functions (CDFs) of the DL and the UL WB SINR performances are shown in Figs. 2(a) and 2(b), respectively.

As can be seen from Figs. 2(a) and 2(b), the straightforward dynamic TDD scheme with no ILIM is actually beneficial for DL transmissions compared to the benchmarking scheme with static TDD. This is because the interference from UEs with relatively low transmission power and high path loss in the UL is usually weaker than that from picocells in the DL. However, the UL WB SINR of the straightforward dynamic TDD scheme takes a serious hit compared with that of the static TDD scheme due to the devastating DL-



(a) CDF of the DL WB SINR



(b) CDF of the UL WB SINR

Figure 2. CDF of the DL and the UL WB SINR

to-UL interference. In order to save the seriously interfered UEs from link failure in the UL, a large reduction on the DL power at BSs, e.g., $\Delta P^{\mathrm{DL}} = -20\,\mathrm{dB}$, is shown to be helpful at the expense of SINR degradation of the non-cell-edge UEs in the DL. An interesting note is that the cell-edge UEs seem to be immune to the negative effect of the DLPR scheme because the benefits of decreased DL interference level generally outweigh the power loss of the useful signals for the interference-limited cell-edge UEs. The CC and ULPB schemes are also proved to be useful to improve the performance in the UL, with little performance degradation in the DL compared with the straightforward dynamic TDD scheme. Finally, the IC scheme brings considerable improvement on the UL WB SINR, especially for the cell-edge UEs. An interesting observation is that the ULPB scheme and the IC scheme seem to complement each other. The ULPB is more effective for cell-interior UEs, while IC is more effective for cell-edge UEs. Hence, combined ILIM schemes are envisaged to be more powerful than individual ones, which will be investigated in following sub-sections.

B. DL/UL UPTs with basic ILIM

In this sub-section, we investigate the performance of DL/UL UPTs for dynamic TDD with various basic ILIM schemes. The periodicities of dynamic TDD reconfiguration are $T_0 = 200\,\mathrm{ms}$ and $T_1 = 10\,\mathrm{ms}$ for comparison purposes. The parameters of all ILIM schemes are the same as those in Section V-A. First, we consider the following schemes with basic ILIM for benchmarking:

- Scheme 1: LTE Release 12 static TDD with TDD configuration #3 [3], where the DL/UL subframe ratio is 7:3
- Scheme 2: LTE Release 12 dynamic TDD (T_0) w/o ILIM
- Scheme 3: LTE Release 12 dynamic TDD (T_1) w/o ILIM
- Scheme 4: Scheme 3 with CC
- Scheme 5: Scheme 3 with DLPR
- Scheme 6: Scheme 3 with ULPB
- Scheme 7: Scheme 3 with IC
- Scheme 8: Hypothetical LTE Release 13 dynamic TDD (T_1) with IC

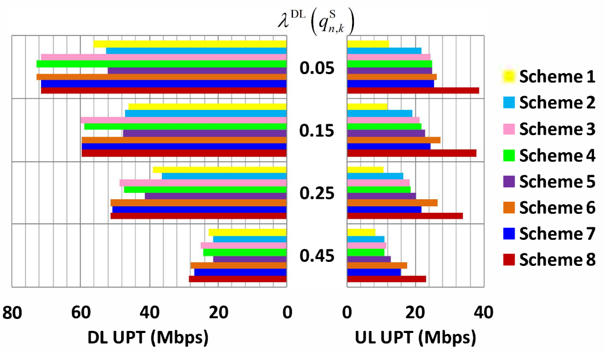
Note that the assumed TDD DL/UL subframe splitting in Scheme 1 matches the ratio of DL/UL traffic arriving rates in case of $T = 10$. In Scheme 8, apart from the existing 7 TDD configurations defined in LTE Release 12, we add another 3 TDD configurations favoring the UL transmissions with DL/UL subframe ratios being 1/9, 2/8, and 3/7, respectively. It should be noted that the DL/UL subframe ratio in LTE Release 12 cannot go below 2/3 [3], while in the hypothetical LTE Release 13 network, the ratio now freely ranges from 1/9 to 9/1. Thus, the system can achieve full flexibility of dynamic TDD configuration.

Figs. 3(a)~3(c) show the performance results of dynamic TDD with basic ILIM in terms of 95-, 50-, and 5-percentile DL/UL UPTs, respectively.

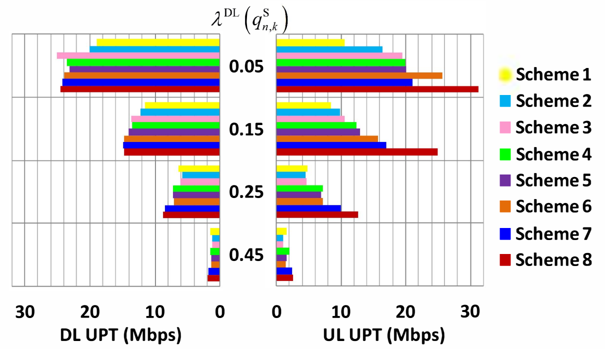
As can be seen from Fig. 3(a), the performance of the 95-percentile DL UPT is much higher than that of the 95-percentile UL UPT because MIMO transmissions can be activated for the cell-interior UEs in the DL when interference is low.

Compared with the baseline scheme with static TDD (Scheme 1), the straightforward dynamic TDD scheme with T_1 (Scheme 3) shows solid gains in most performance categories. However, it shows a large performance degradation of more than 60 % in terms of the 5-percentile UL UPT when the traffic load is medium to high, e.g., $\lambda^{\mathrm{DL}}(q_{n,k}) > 0.15$. This is due to lack of ILIM to mitigate the DL-to-UL interference. Moreover, a faster dynamic TDD configuration time scale (Scheme 3) is shown to outperform a slower one (Scheme 2), as previously reported in [4].

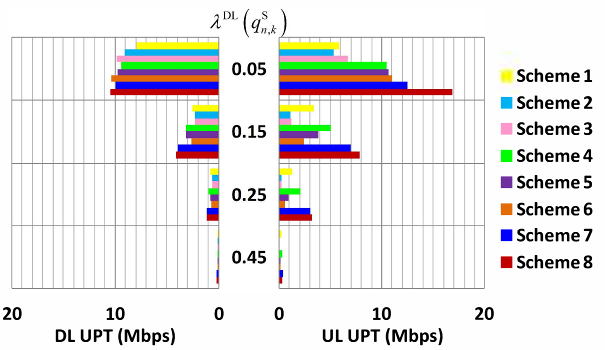
Regarding the basic ILIM strategies, the CC scheme (Scheme 4) brings a considerable improvement of more than 50 % on the 5-percentile UL UPT compared with the straightforward dynamic TDD (Scheme 3), at the expense of minor sacrifice in DL UPTs. However, the effectiveness of the CC scheme declines when the traffic load is medium to high, e.g., $\lambda^{\mathrm{DL}}(q_{n,k}) = 0.25 \sim 0.45$, because the flexibility of dynamic TDD is compromised considering that all the small cells in a cluster adapt their TDD configuration according to the aggregated traffic in the cluster rather than to their individual traffic conditions. The DLPR scheme (Scheme 5) is shown to noticeable outperform the CC scheme (Scheme 4), but with an alarming performance deterioration of around 20 % in the 95-percentile DL UPT compared with Schemes 3 and 4. This is due to the poor performance of the DL WB SINR shown in Fig. 2(a), which greatly hinders the



(a) 95-percentile DL and UL UPTs (basic ILIM)



(b) 50-percentile DL and UL UPTs (basic ILIM)



(c) 5-percentile DL and UL UPTs (basic ILIM)

Figure 3. DL and UL UPTs (basic ILIM)

MIMO operation in the DL. The ULPB scheme (Scheme 6) is shown to be quite useful when the traffic load is low, e.g., $\lambda^{\mathrm{DL}}(q_{n,k}) = 0.05$. However, with a heavier traffic load, the cell-edge UEs suffer from large performance degradation since the power headroom of a cell-edge UE tends to be quickly drained up and increasing UL power leads to more serious UL interference. The IC schemes (Schemes 7 & 8) are proved to be very effective, especially when the traffic load is not heavy, e.g., $\lambda^{\mathrm{DL}}(q_{n,k}) < 0.45$. Scheme 8 with full flexibility of dynamic TDD configuration can even achieve remarkable gains around 30 % and 200 % for the DL and the UL UPTs, respectively, when $\lambda^{\mathrm{DL}}(q_{n,k}) = 0.05$.

C. Impact of 256QAM on DL/UL UPTs

The ULPB scheme was reported to be less effective in [6] than in our study. This is because the ULPB scheme in [6] was not allowed to use 256QAM, and suffered from modulation saturation at 64QAM. In Table II, we present the UL UPT results for Schemes 3 and 6 with and without 256QAM when $\lambda^{\mathrm{DL}}(q_{n,k}) = 0.05$. As can be observed from Table II, without 256QAM, the performance gains of the ULPB scheme (Scheme 6) over the straightforward dynamic TDD scheme (Scheme 3) is around 0 % and 3.3 % in terms of the 95- and 50-percentile UL UPTs, respectively, while the corresponding gain in terms of the 5-percentile UL UPT is around 60 %. In contrast, with 256QAM, Scheme 6 results in about 7.56 %, 30 % and 64 % higher performance than Scheme 3 in terms of the 5-, 50- and 5-percentile UL UPTs, respectively, showing the benefits of 256QAM. However, it is important to note that Scheme 6 provides a moderate gain of 7.56 % with respect to Scheme 3 in terms of the 95-percentile UL UPT. This is because 256QAM may still underestimate the achievable UL UPT of the cell-interior UEs in Scheme 6. The modulation ceiling created by 256QAM may also occur for Schemes 7 and 8. Thus, an even higher modulation scheme than 256QAM may be required, e.g.,1024QAM, though its implementation feasibility is currently unclear due to the error vector magnitude (EVM) issues at transmitters [1].

D. DL/UL UPTs with combined ILIM

Based on the above discussion, we can find that the DLPR scheme (Scheme 5) is inferior to other ILIM schemes in almost every performance category. Therefore, we will dismiss the DLPR scheme from the following investigation on combined ILIM strategies. As a result, we round up several dynamic TDD schemes with combined ILIM as follows,

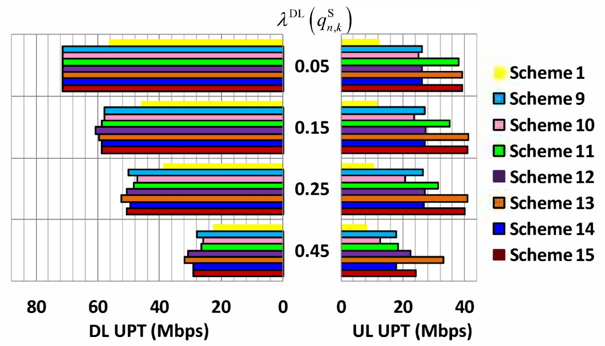
- Scheme 9: Combined Schemes 4 and 6
- Scheme 10: Combined Schemes 4 and 7
- Scheme 11: Combined Schemes 4 and 8
- Scheme 12: Combined Schemes 6 and 7
- Scheme 13: Combined Schemes 6 and 8
- Scheme 14: Combined Schemes 4, 6 and 7
- Scheme 15: Combined Schemes 4, 6 and 8

Figs. 4(a)~4(c) show the performance results of dynamic TDD with combined ILIM in terms of 95-, 50-, and 5-percentile DL/UL UPTs, respectively.

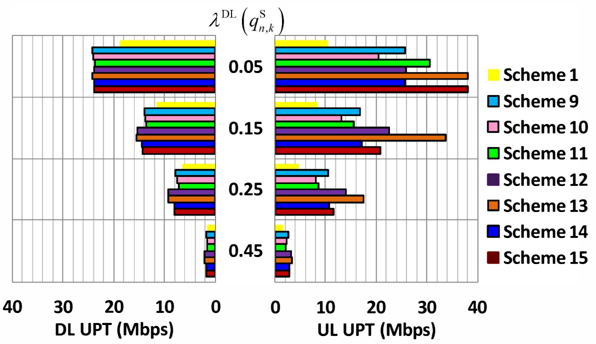
As can be observed from Figs. 4(a)~4(c), the combination scheme of CC and IC (Scheme 10) is strictly inferior to the combination scheme of CC and ULPB (Scheme 9), because the CC scheme already eliminates a few strong interfering small cells for the UL, and thus IC only treats minor interferers in Scheme 10. On the other hand, in Scheme 9, on top of CC, UEs are granted to use a larger power that leads to a better performance. When the traffic load is not heavy, e.g., $\lambda^{\mathrm{DL}}(q_{n,k}) < 0.45$, Scheme 9 greatly outperforms the static TDD scheme (Scheme 1) by around 20~40 % and 100~140 % in terms of the DL and the UL UPTs, respectively. The combination scheme of CC and IC with the hypothetical LTE Release 13 dynamic TDD (Scheme 11) outperforms or shows comparable performance as Scheme 9 because of the full flexibility of dynamic TDD configuration.

Table II
COMPARISON OF THE UL UPT (W/ OR W/O 256QAM)

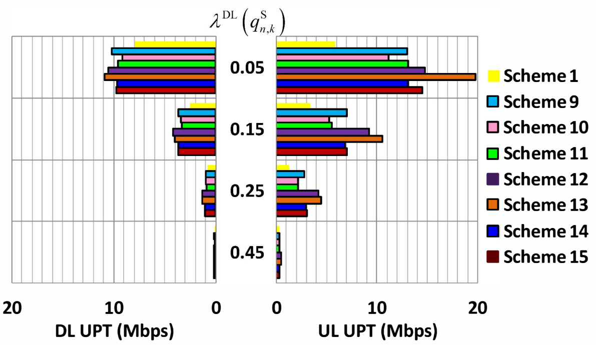
Schemes	95%-tile UL UPT (Mbps)	Relative gain	50%-tile UL UPT (Mbps)	Relative gain	5%-tile UL UPT (Mbps)	Relative gain
Scheme 3 (w/o 256QAM)	19.42	-	18.52	-	5.85	-
Scheme 6 (w/o 256QAM)	19.42	0%	19.14	3.35%	9.32	59.32%
Scheme 3 (w/ 256QAM)	24.47	26.00% (-)	19.51	5.35% (-)	6.73	15.04% (-)
Scheme 6 (w/ 256QAM)	26.32	35.53% (7.56%)	25.64	38.44% (31.42%)	11.02	88.38% (63.74%)



(a) 95-percentile DL and UL UPTs (combined ILIM)



(b) 50-percentile DL and UL UPTs (combined ILIM)



(c) 5-percentile DL and UL UPTs (combined ILIM)

Figure 4. DL and UL UPTs (combined ILIM)

The combined ULPB and IC schemes (Schemes 12 & 13) seem to be the most powerful combinations, which substantially increase the UL performance due to the larger transmit power at UEs and the IC capabilities at BSs. Some of the tremendous performance gain in the UL is also shown to be transferred to the DL by means of the traffic-adaptive dynamic TDD scheduling. To be more specific, since the performance in the UL is enhanced, some UL subframes can be transformed into DL subframes thus improving the DL performance. When the traffic load is low to medium, e.g., $\lambda^{DL}(q_{n,k}) = 0.05 \sim 0.15$, Scheme 13 is shown to immensely outperform the static TDD scheme (Scheme 1) by approximately 30~60 % and 210~300 % in terms of the DL and the UL UPTs, respectively.

Finally, the combination of all three ILIM schemes (Scheme 14) only gives similar performance compared with the combination of CC and ULPB (Scheme 9). Only with the hypothetical LTE Release 13 dynamic TDD activated can the full combination scheme (Scheme 15) outperform Scheme 9 in the UL. This is because the CC scheme is not very compatible with the IC scheme, i.e., the CC scheme eliminates dominant interfering small cells for the UL, rendering the IC process less effective.

To sum up, if it is preferable to find an easy-to-implement scheme with reasonable performance gains, Scheme 9 should be called upon. But if complexity issue is a minor concern, Scheme 12 or 13 should be engaged to realize the full potential of dynamic TDD.

VI. CONCLUSION

In this paper, we present new results on dynamic TDD transmissions in homogeneous small cell networks. Various kinds of ILIM schemes, as well as their combinations have been investigated. Moreover, the impact of high-order modulation schemes on dynamic TDD is studied. The combination of CC and ULPB is recommended for low-complexity implementation, while that of ULPB and IC can bring more performance gains at the expense of higher complexity.

ACKNOWLEDGEMENT

The authors would like to thank Jian Huang and Ruiqi Xue from Shanghai Jiao Tong University for their selfless assistance in the simulations.

REFERENCES

[1] ETSI MCC, Draft Report of 3GPP TSG RAN WG1 #75. Nov. 2013.
[2] 3GPP, "TR 36.828 (V11.0.0): Further enhancements to LTE Time Division Duplex (TDD) for Downlink-Uplink (DL-UL) interference management and traffic adaptation," Jun. 2012.
[3] 3GPP, "TS 36.213 (V11.2.0): Physical layer procedures," Feb. 2013.
[4] Z. Shen, A. Khoryaev, E. Eriksson, X. Pan, "Dynamic uplink-downlink configuration and interference management in TD-LTE," IEEE Communications Magazine, vol. 50, no., 11, pp. 51-59, Nov. 2012.
[5] Sharp, "R1-132350: DL power control based interference mitigation for eIMTA," 3GPP RAN1 Meeting #73, Fukuoka, Japan, May, 2013.
[6] Sharp, "R1-132351: UL power control based interference mitigation for eIMTA," 3GPP RAN1 Meeting #73, Fukuoka, Japan, May, 2013.
[7] 3GPP, "TR 36.814 (V9.0.0), Further advancements for E-UTRA physical layer aspects," Mar. 2010.
[8] 3GPP, "TS 36.104 (V11.4.0), Base Station (BS) radio transmission and reception," Mar. 2013.