Dynamic TDD for LTE-A and 5G

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Abstract
In recent years, mobile communication traffic has continuously been shifting from being dominated by voice-call traffic with symmetric uplink / downlink capacity requirements to burst-like traffic with strongly fluctuating capacity requirements depending on instantaneous file upload / download activities by mobile users. Consequently, LTE, which was originally designed with fixed FDD or TDD modes with little flexibility for varying the capacity split between uplink and downlink, is being augmented with features that allow for more flexible use of radio resources. One of these features is "enhanced Interference Mitigation and Traffic Adaptation" (eIMTA) which notably allows for very dynamic adaptation of the TDD pattern e.g. in response to varying capacity requirements in uplink and downlink. eIMTA was standardized in LTE-A Release 12 and eIMTA-like functionality is considered to be one of the key enablers for 5G technologies.

The purpose of this paper therefore is to shed some light on eIMTA, its main characteristics and capabilities and to illustrate its behaviour by means of system-level simulations.

Introduction
From day 1 LTE was designed to support both frequency division duplex (FDD) and time division duplex (TDD) in a single specification. While focus had been mostly on FDD, TDD gains importance for small cell deployments or deployments in higher frequency bands. Having been designed initially for classical full coverage macro-cell deployments, TDD in LTE was rather rigid, i.e. a static TDD pattern was expected to be selected for the complete network. A major drawback of such network configurations is that the allocation of radio resources to uplink and downlink is very rigid, so rapid adaptation to instantaneous fluctuations in the uplink / downlink load situations was hence not possible. Accordingly related signalling was also defined in manner not apt to support this.

However, in recent years, small-cell deployments have been identified as a primary means to increase network capacity. Based on their short reach, small cells typically do not inflict significant interference onto each other. Based on this decoupling, cell-specific TDD pattern selection becomes feasible. Dynamic TDD also appears to be very attractive considering the typically small number of simultaneously active UEs in a small cell. Imagine a small cell with only a single active user in it; it is quite obvious that data rates experienced by the user could be improved drastically by adapting the TDD pattern depending on whether the user predominantly wants to transmit up- or download data at a particular point of time. Based on this reasoning several 5G candidate technologies for small-cell deployments feature very flexible dynamic TDD schemes, cf. e.g. [1]. For reasons of backward compatibility with legacy UEs, it is not possible to implement an equally flexible solution in LTE. Nonetheless, release 12 of the LTE standard introduces support for more rapid TDD configuration [2]; there it is called "enhanced Interference Mitigation and Traffic Adaptation" (eIMTA).

The need for backward compatibility with pre-release-12 equipment imposes significant constraints on features that can be implemented and related signalling and measurements making implementation of eIMTA a rather complex endeavour. The purpose of this paper is to shed some light on crucial technological aspects of eIMTA related to layer 1/2 procedures such as grant and HARQ timing and channel measurements.

eIMTA in LTE

Flexible TDD

In TDD in general, each Transmission Time Interval (TTI) the transmission is pre-configured for downlink (D), for uplink (U) or to be switched (S) from downlink to uplink. LTE supports 7 different TDD patterns which offer uplink / downlink ratios from approximately 60:40 to 10:90 within a system-frame consisting of 10 successive TTIs [3].

Table 1 LTE TDD configurations.

TDD Conf	TTI index									
	0	1	2	3	4	5	6	7	8	9
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

Any new scheme will be restricted to switching between these TDD patterns. For UEs supporting future eIMTA implementations flexible sub-frames as illustrated by "F" in Table 2 are introduced. These can be configured dynamically either for uplink or for downlink. Legacy UEs will be configured with an uplink-heavy TDD configuration (in particular the "UL HARQ reference configuration", e.g. 0, see below) and are thus limited to uplink transmission in the flexible subframe. The eNB will not schedule a legacy UE with an uplink grant in case it wants to use the subframe for an eIMTA UE in the downlink. For the eIMTA UEs an eNodeB can at best adapt its TDD pattern every 10ms; adaptations within a system-frame are not possible. But, even arbitrary switching between any of the 7 TDD patterns is only feasible in certain eIMTA configurations as will become clear below.

Table 2 Effective eIMTA Frame Structure.

TTI index									
0	1	2	3	4	5	6	7	8	9
D	S	U	F	F	D	S/D	F	F	F

For the actual choice of the TDD pattern in a particular cell and for a particular system-frame various criteria are conceivable and the algorithm design lies within the responsibility of the vendor or operator. Typical criteria are—as suggested by the feature's name—either targeting interference mitigation (IM) and/or adaptation to varying traffic loads.

RRM Timing and Reference Configurations

Timing of usage of HARQ processes, grants and HARQ feedback is a challenging topic by itself. In TDD, uplink and downlink control information such as HARQ acknowledgements (ACKs) and not acknowledgements (NACKs) cannot be sent instantaneously like in FDD and need to wait until the next transmission opportunity. The bundling of ACK/NACKs is also limited by the restrictions of the control channel capacity. For eIMTA, it becomes even more complicated in combination with the constraints from the requirement of backward compatibility with pre-release 12 UEs.

For dealing with this, the concept of "HARQ reference configurations" has been introduced. In consequence, the system basically has to deal with three different TDD configurations in eIMTA operation:

- DL HARQ reference configuration
- UL HARQ reference configuration and
- Scheduling TDD configuration

The DL HARQ reference configuration is a downlink-heavy TDD configuration that defines characteristics of the control signalling (PUCCH) in the uplink, such as timing of the HARQ feedback corresponding to DL transmissions. This is based on the definition that sub-frames assigned to the uplink in this reference configuration will be—regardless of the instantaneous eIMTA adaptation—uplink sub-frames for sure.

Similarly, the UL HARQ reference configuration is an uplink-heavy TDD configuration, with the characteristic that sub-frames that are downlink sub-frames in this TDD pattern are downlink sub-frames for sure, irrespective of fast eIMTA adaptation. Hence, it defines in which sub-frames an UE will receive layer-1 control signalling corresponding to uplink data transmissions. Furthermore, the UL HARQ reference configuration defines the number and timing of UL HARQ processes. So even when scheduling is currently done according to a TDD pattern that is different from this reference configuration, the HARQ processes in the uplink are to be assigned according to this reference configuration.

Both these reference configurations are configured on a relatively slow time scale using dedicated higher layer signalling and SIB-1 signalling, respectively.

The scheduling TDD configuration is the TDD configuration that is actually used in the cell to indicate, which sub-frames are to be used for uplink and downlink transmissions, respectively. This is what can be adapted on a fast time scale at most at system-frame rate. At this the selection is constrained by the two reference configurations defining the sub-frames that have to be fixed uplink and downlink sub-frames and which sub-frames are flexible. A couple of examples:

- If the downlink and uplink reference configuration are TDD configurations #5 and #0, respectively, any TDD configuration #0…#6 can be selected as scheduling TDD configuration.
- If the downlink and uplink reference configuration are TDD configurations #5 and #1, respectively, only TDD configuration #1, #2, #4 and #5 can be selected as scheduling TDD configuration.
- A combination of downlink and uplink reference configurations of #4 and #2, respectively, is not permitted as there is no TDD configuration satisfying the constraints imposed by both HARQ reference configurations.

It can be seen that a downlink / uplink reference configuration pair [#5, #0] offers the greatest flexibility in traffic adaptation. However, there are disadvantages such as increased uplink HARQ round-trip times as the number of uplink HARQ processes is maximized by this configuration, and possibly drastically increased inter-cell interference fluctuation caused by a mix of uplink and downlink transmissions in a larger set of flexible sub-frames.

For UEs that are not eIMTA-capable (Rel. 11 or older) the uplink HARQ reference configuration is used as the only TDD configuration as in fixed TDD operation. Obviously, such UEs can only be scheduled for downlink transmissions in fixed downlink sub-frames while uplink transmissions in flexible sub-frames are allowed.

Means of Interference Mitigation

As mentioned above, cell-specific TDD pattern selection introduces the problem of cross-link interference between neighbouring cells and with this potentially severe variations in interference power / SINR between successive TTI even when the radio channel itself does not change. Without any specific action, this can seriously deteriorate the performance of the link adaptation and hence the user experience.

<u>Measurement Constraints</u>

Even if no action is taken to combat or avoid this interference fluctuation, the system should at least be aware of such SINR fluctuations. Hence, 3GPP introduced separate CSI measurements as a feature for eIMTA. With this, the eNodeB can instruct the UE to perform two separate downlink measurements in two subsets of TTI. Expediently, these subsets are disjoint containing the fixed downlink and flexible TTI, respectively. Similarly, the eNodeB is at liberty to distinguish between uplink channel measurements taken during fixed or flexible TTI in order to obtain more reliable CSI information for the different sub-sets of TTIs. Depending on whether the TTI to be scheduled is a fixed or flexible TTI, the latest CSI information for fixed or flexible TTIs shall be used, respectively.

While this is not perfect as cells have more flexibility than choosing from configurations #0 and #5 and hence not all flexible TTIs in a frame are always jointly assigned to uplink or downlink only, this approach with two separate CSI measurements constitutes a valid compromise to combat the worst degradation in link adaptation efficiency caused by significant differences in inter-cell interference caused by uplink and downlink transmissions, respectively.

Enhanced Uplink Power Control

Uplink power control in LTE is typically configured in a way that the power received by the eNodeB is not too high compared to the noise floor, reasons being (i) saving of UE battery power, (ii) avoidance of severe uplink inter-cell interference due to time- and frequency-selective scheduling and (iii) the dynamic range of the Analog Digital Converter. Typical downlink power settings, however, are such that DL-to-UL cross-link interference may completely drown uplink signals.

Hence, in flexible TTIs use of higher uplink transmission power levels are advisable. In order to save UE battery power as far as possible, 3GPP introduced the option to have two separate power control settings in parallel. Expediently, the typical low uplink power level will be used for fixed uplink TTIs, whereas for uplink transmissions in flexible uplink TTIs a higher power level is configured, e.g. by means of a higher secondary value of P_{0_PUSCH}, to reduce the UL/DL power imbalance.

Cell Clustering

For clusters of dense small cell networks it may still be advantageous to synchronize the selection of TDD patterns among neighboring cells. As long as such sets consist of only a small number of cells the system can still adapt to specific instantaneous traffic characteristics of a small set of UEs.

A typical and simple approach for clustering is to let eNodeBs perform measurements on the signal strength of the neighboring cells and select a common scheduling TDD configuration for all cells whose inter-eNodeB signal strength lies above a certain threshold. For this purpose 3GPP standardized an X2 message for inter-cell interference coordination by means of which an eNodeB can inform others about its intended scheduling TDD configuration. Proprietary solutions to coordinate between eNodeBs of the same vendor are of course not constrained by this.

Performance Analysis

In this section, we present some simulation results to support the above discussion.

As pointed out above, eIMTA is particularly apt for use in small-cell deployments. Hence, 3GPP also designed its test scenarios accordingly. In this paper, we focus on scenario 2 of [4] with drop model 4b of [5], where in each macro cell 4 small cells are uniformly distributed and 10 UEs are clustered around each of the small cells. Constraints of the drop model prevent small cells from being extremely close to each other or to the macro cell. The macro cells and their UEs are assumed to be operating on a separate carrier and are hence not simulated. For a comprehensive summary of the simulation parameters cf. Table 6.3-1 of [4]; we selected the 2:1 DL:UL traffic load asymmetry and FTP model with 0.5MB file size.

Downlink and uplink reference configuration are configured as TDD configurations #5 and #0, respectively; hence any TDD configuration #0…#6 can be selected as scheduling TDD configuration. To select the scheduling TDD configuration, we use a simple buffer status criterion

$$required\ UL\ percentage = \frac{2 \times \sum_{\forall\ \mathrm{UEs}} \#\ UL\ bits}{\sum_{\forall\ \mathrm{UEs}} (2 \times \#\ UL\ bits + \#\ DL\ bits)} \qquad (1)$$

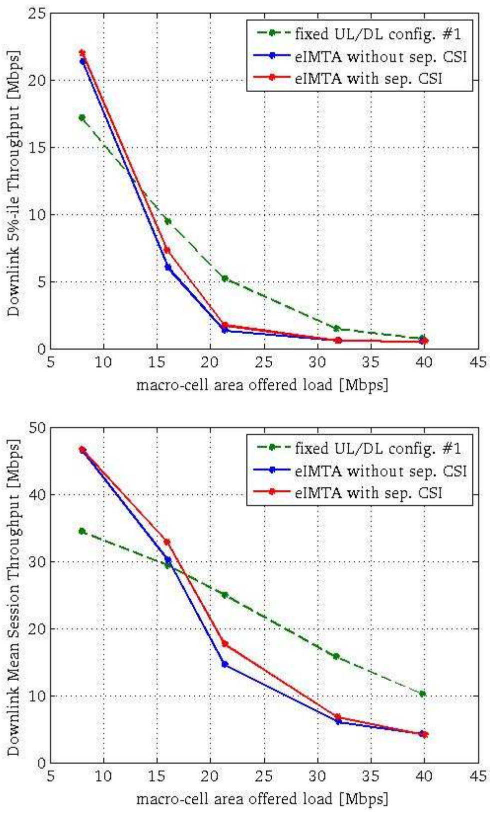

Figure 1 DL session throughput for flexible TDD w/ and wo/ secondary CSI measurements.

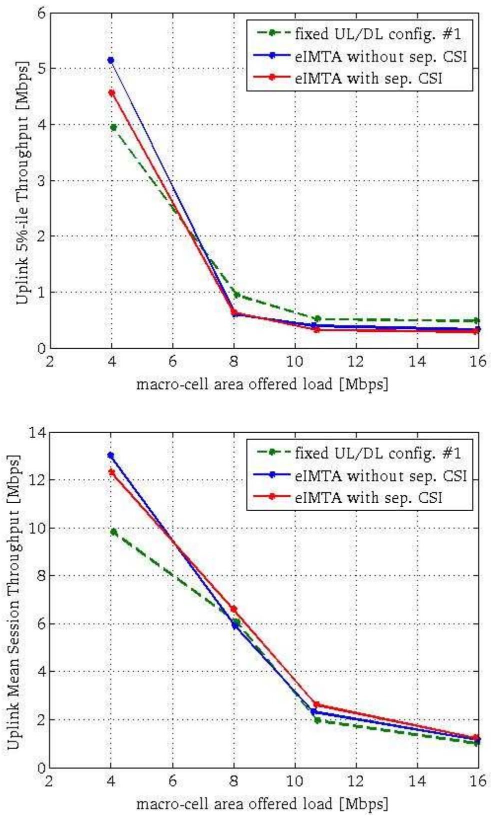

Figure 2 UL session throughput for flexible TDD w/ and wo/ secondary CSI measurements.

which we evaluate either per eNodeB or—in case of clustering—per cluster and round up in favour of the uplink, every 10ms.

Let us first consider a comparison of plain eIMTA with and without separate CSI measurements for fixed and flexible TTIs, with fixed TDD with configuration #1 as reference in Figure 1 and Figure 2.

At low load, we observe considerable gains in performance due to the flexibility in adapting to instantaneous traffic load. The separate CSI measurements for fixed and flexible TTIs also improve system performance considerably. However, in higher load, we observe an overloading of the uplink, which now also harms the downlink such that downlink performance even falls below that of fixed TDD, as our TDD pattern selection criterion puts emphasis on the uplink.

The effect of a secondary uplink power control for the flexible TTIs can be observed in Figure 3. Increasing the target power density parameter P_{0_PUSCH} from -76dBm to -70dBm improves uplink performance while hardly harming the downlink (not shown). Increasing uplink power further does not yield added benefit in uplink performance while at the same time degrading downlink performance more notably; the thereby increasing interference fluctuation from varying uplink allocations even harms uplink performance.

Clustering is an interesting topic. While we already noticed a strong coupling between uplink and downlink for plain flexible TDD, more UEs are

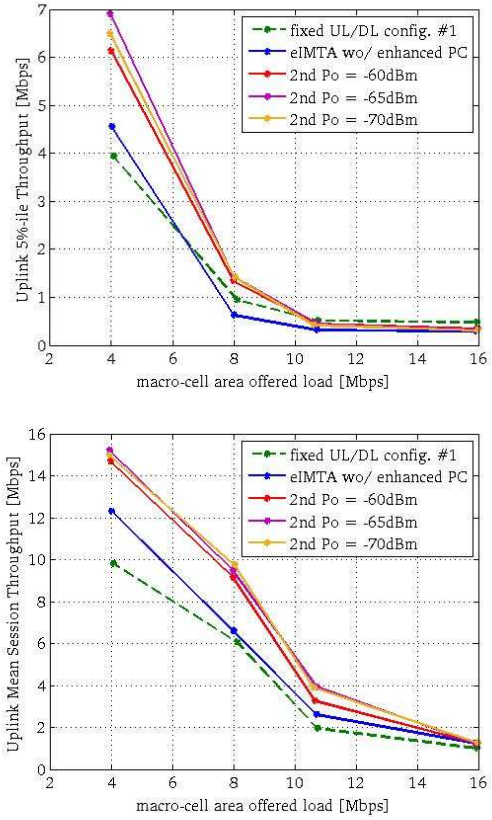

Figure 3 UL session throughput as function of uplink power control settings.

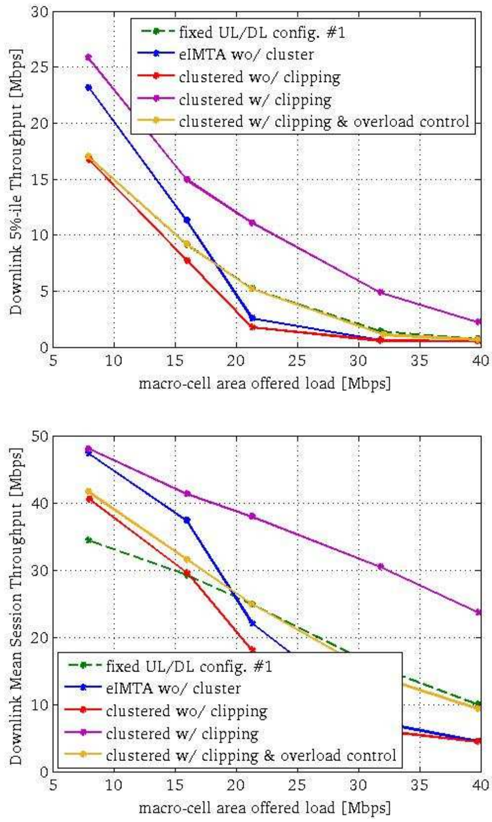

Figure 4 DL session throughput w/ and wo/ clustering.

brought together in a decision criterion when clustering is involved. Hence, there is even more room for prioritizing certain traffic flows (e.g. UL vs. DL, mean vs. cell-edge user experience, etc.). Seemingly small changes in the criteria used for clustering or TDD pattern selection can lead to drastic changes in system behaviour.

Here, we deployed a simple pathloss-based clustering approach, where all eNodeBs that have a mutual pathloss lying below a certain threshold (even in a chain-like manner) are grouped together. A scheduling TDD pattern is then selected based on the above buffer-status based criterion (1) jointly for all cells in a cluster. At this, clustering is limited to small cells belonging to the same macro eNodeB, thereby justifying our centralized TDD pattern selection approach.

The red line in Figure 4 and Figure 5 represents this approach. Here, the downlink suffers greatly while the uplink exhibits considerable improvement as more uplink-oriented TDD patterns are selected.

If we modify the TDD pattern selection slightly by introducing a buffer clipping criterion in a way that the buffer status levels are clipped prior to evaluation of (1) to what can be expected to actually be transmitted before the packet discard timer strikes[1], the situation in terms of gains is

[1] In line with 3GPP assumptions this happens after 8 seconds in our simulations.

novel
mobile
radio

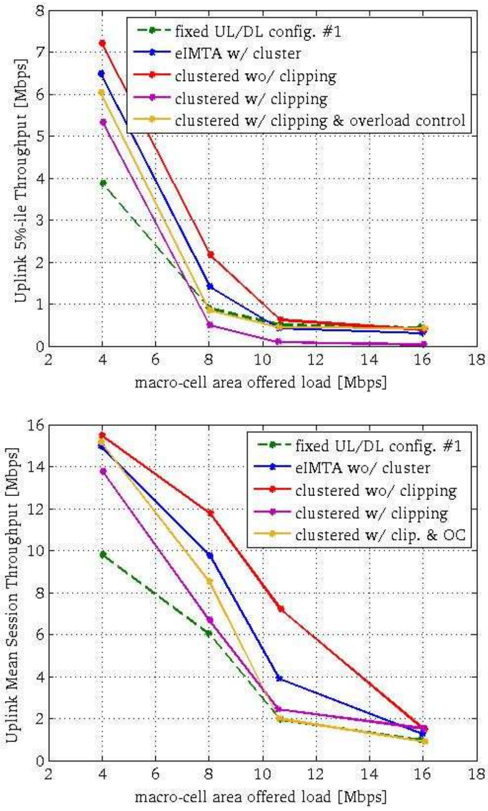

Figure 5 UL session throughput w/ and wo/ clustering.

reversed (purple line). This modification prevents an overloaded uplink from destroying downlink performance. Significant uplink gains are then only visible at low loads.

Another scheme tries to better balance uplink and downlink performance (ochre line). Here—on top of the above clipping approach—we fall back to TDD configuration #1 (60% downlink) whenever uplink and/or downlink are found to be (temporarily) overloaded. Accordingly, in high-load scenarios, this scheme exhibits almost identical performance as fixed TDD, while at lower load moderate gains from flexible TDD pattern selection are visible.

These were only some simple examples of criteria for eIMTA and it became apparent that there is plenty of room for optimization towards certain targets of performance or fairness.

Summary

In this paper, dynamic TDD in the context of the LTE-Advanced Release 12 feature "enhanced Interference Mitigation and Traffic Adaptation" (eIMTA) is explained in detail. This scheme allows for flexible utilization of the available radio resources by means of dynamic adaptation of the TDD uplink / downlink subframe configuration thereby greatly improving user experience especially in low to medium load.

Some important aspects of eIMTA, namely flexible TDD pattern selection, separate CSI measurements, enhanced uplink power control and clustering, were discussed and evaluated by means of system-level simulations. Packet throughput gains for the small cell scenarios as reported by 3GPP in [4] are confirmed. Nevertheless, it was observed that great care must be taken in designing the eIMTA system in order to benefit from it and to have a good balance between uplink and downlink performance and to ensure fairness among UEs in the system.

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