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# Dynamic TDD in LTE small cells

Jussi Kerttula<sup>\*</sup> , Aleksi Marttinen, Kalle Ruttik, Riku Jäntti and Mirza Nazrul Alam

## Abstract

Dynamic time-division duplexing (TDD) enables adjustments of uplink (UL) and downlink (DL) resources flexibly according to the instantaneous traffic load. Long-Term Evolution (LTE) systems can be implemented in TDD mode (TD-LTE). However, the dynamic change of a TDD configuration has not been well supported and investigated. In large macro cells, the high transmit power of base stations (BSs) easily blocks the weaker user equipment's (UE) UL signal (called the UL-DL interference); and therefore, neighboring cells usually operate with the same TDD configuration. In small cells, such as femtocells, the BS and UE transmission powers are in the same order and the system can afford to have overlapping UL-DL subframes. In addition, when DL load is light, the BS transmits empty DL subframes with only a reference signal (RS). In this paper, we measured the interference caused by DL RS. This interference is not negligible; and therefore, it is beneficial to reduce the amount of DL subframes by switching lightly loaded BSs to UL-heavy subframe configuration. We illustrate with simulations that this can improve system efficiency. Changing the subframe configuration dynamically has a switching-related cost. Frequent switching between subframe configurations can actually decrease throughput. We describe conditions where configuration change is beneficial. We also propose an algorithm that decreases the switching overhead and improves the ability to adapt to varying loads.

**Keywords:** TD-LTE, Dynamic TDD, Small cells, HARQ process, Reference signal interference, Subframe configuration change

## 1 Introduction

Time-division duplexing (TDD) separates downlink (DL) and uplink (UL) signals in time. The amount of time slots in each direction can be asymmetric and be changed dynamically leading to a significant increase in network bandwidth efficiency [1].

Dynamic TDD can lead to overlap in neighboring cell's UL and DL transmissions. This is problematic especially in large cells where a high power DL signal blocks the weaker UL signal. Therefore, large cells usually use the same UL/DL configurations. In small indoor cells (femtocells), the DL signal power is of the same order as the UL signal. The difference in interference between DL and UL is small, and we have the freedom to choose UL/DL configuration for each BS independently.

In this paper, we investigate the use of dynamic TDD in TD-Long-Term Evolution (LTE) small cells. We utilize the TD-LTE test platform [2] and study the impact of dynamic TD-LTE subframe configuration on different system levels. The platform enables us to observe more

static effects such as interference level for a certain configuration, but also to follow temporal effects when changing UL/DL configuration.

Most dynamic TDD analysis studies system interference conditions with different UL/DL configurations and assumes that the UL/DL configuration is changed instantaneously [3–5]. Moreover, interference is usually modeled by an ON/OFF model. When data is transmitted (ON state), interference is generated, and when there is no data transmission (OFF state), there is no interference. However, LTE base stations (eNodeBs) always transmit a reference signal (RS) in the DL. The RS is sent even if there is no payload to be transmitted. RSs cause interference, but the impact is often forgotten in TD-LTE analysis [6, 7]. We measure this interference in the test platform and, based on these measurements, propose a simple extended interference model for the system-level studies. We use the proposed interference model in system level simulation and quantify the effect of the RS interference in an indoor environment.

The RS-induced interference can be reduced when the eNodeB switches to UL-heavy UL/DL configuration

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whenever possible. The main difference compared to previous studies is that we consider the cost of switching. Before the new configuration can be used, the transmissions using the previous configuration have to be ended. The switching cost can be tracked down to the large time frame required for the configuration change and the time needed for finishing the hybrid automatic repeat request (HARQ) processes [3]. We analyze when the switching cost reduces capacity, model the scenario when switching UL/DL configuration is beneficial, and propose an algorithm that reduces switching cost in an LTE system.

The organization of this paper is as follows: In Section 2, we discuss the dynamic TDD in LTE and present a brief review on the subject. In Section 3, we present our results and discuss interference measurements when two eNodeBs are operating on different UL/DL configurations simultaneously. System level interference simulations are presented and discussed in Section 4. In Section 5, we discuss the dynamic UL/DL configuration procedures and study the cost of the configuration change. Section 6 concludes the article.

## 2 Overview of dynamic TD-LTE

Currently, one of the most popular wireless communication systems is LTE. The TDD LTE (TD-LTE) allocates resources based on 1 ms subframes. TD-LTE in 3GPP Release 8 supports seven UL/DL subframe configurations as shown in Table 1. Together with different special subframe configurations, it is possible to have from 11 to 63 % of time reserved for UL transmissions. This allows the network to cope with asymmetric traffic loads. The UL-to-DL traffic ratio is globally 1:3.29; however, there are variations depending on the continent [8]. The first LTE releases (Releases 8–11) expected that UL/DL configuration would not be changed dynamically, and the chosen configuration would be constant over the whole network. Therefore, those releases do not discuss dynamic TDD changes. Later releases support to the dynamic TD-LTE has continuously evolved. For instance, in Release 12, a novel method for faster subframe allocation was introduced. This method will be described in Section 2.1.2.

Dynamic TDD has been studied widely. Several articles have investigated how to match subframe configuration to the instantaneous traffic demand. In [4], El Bamby et al. proposed a distributed resource adaptation scheme which considers both UL and DL traffic loads. Based on that information and the interference from the neighboring small cells, the scheme selects a sufficient UL-DL switching point (i.e., how to split the time between UL and DL). The simulation results show gains of up to 200 %. In [5], a cooperative decentralized scheme for small cell networks was presented. The cooperation is done by sharing UL/DL configuration and other information between neighboring base stations. However, these studies are not considering a real LTE system.

The impact of the interference in a small cell wireless network using dynamic TDD has been discussed in [9]. The study is done in a general TDD network omitting some of the key features related to dynamic TD-LTE that we present in this paper. The analytical results there show that if fair resource allocation is used, the inter-cell-interference does not affect the switching point allocation algorithm. It is also investigated how the link load affects the link throughput. The throughput is analyzed for proportionally fair and interference aware scheduling. The throughput gains are especially good for low load conditions. With high link load, there is no significant difference between the performance of fixed and flexible switching-point methods.

In [10], a dynamic TDD adjustment in outdoor LTE picocells was discussed. The results of this paper indicate that, in a TD-LTE network, dynamic subframe configuration provides major performance benefits. The gains are most significant with low and medium traffic loads. An extensive overview of dynamic TD-LTE including performance evaluation of an outdoor picocell scenario is provided in [3]. It shows that significant performance gains can be achieved with dynamic TDD. The potential throughput drop during the configuration change process is mentioned, but it is not taken into account in the throughput performance evaluation. In this paper,

**Table 1** LTE subframe configurations

Uplink-downlink configuration	Downlink to uplink Switch-point periodicity (ms)	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5	D	S	U	U	U	D	S	U	U	U
1	5	D	S	U	U	D	D	S	U	U	D
2	5	D	S	U	D	D	D	S	U	D	D
3	10	D	S	U	U	U	D	D	D	D	D
4	10	D	S	U	U	D	D	D	D	D	D
5	10	D	S	U	D	D	D	D	D	D	D
6	5	D	S	U	U	U	D	S	U	U	D

we investigate how the configuration change affects the throughput.

Analytical studies confirm the promising performance gains of dynamic TDD. Lassila et al. proposed a novel dynamic scheduling scheme (Dynamic-PS) in [11] and provided an analytical model of it. The aim of the Dynamic-PS was to allocate communication resources based on the number of active flows.

In [12], various interference management strategies are studied in dynamic TDD small cell networks. The considered interference management strategies are cell clustering (CC), interference cancellation (IC), DL power reduction, UL power boosting (ULPB), and a combination of these. The conclusion of this research is that a combination of CC and ULPB is recommended due to the simplicity of the implementation. However, the best performance is achieved with a more complex solution, which is when the combination of ULPB and IC is utilized.

All the abovementioned analysis overlooks two LTE-related important aspects of dynamic TDD. First, because of RS, all DL subframes generate interference even if they do not carry any payload data. Second, UL/DL configuration change is not instantaneous. Transition from one configuration to other has cost, and if done too frequently, the system capacity can actually be reduced.

## 2.1 TDD configuration change

### 2.1.1 Changing the subframe configuration in Release 8

First LTE releases do not specify explicitly how the UE has to operate during a UL/DL configuration change. A network can change configuration at the modification period boundary. The network informs users about possible changes at that boundary by a paging message. The modification period can vary from 640 to 10,240 ms. After receiving a paging message from the eNodeB, the UE seeks TDD configuration information from the SystemInformationBlock1 (SIB1) message. This message is repeatedly transmitted with 80 ms periodicity. The UE continues to use the old system information until it receives a new message. The specifications state that the UE may apply the received system information immediately after it is received [13].

### 2.1.2 eIMTA in Release 12

In LTE Release 12, an enhanced interference mitigation and traffic adaptation (eIMTA) was introduced to allow very dynamic and fast adaptation of UL/DL subframes according to present load. In order to maintain backward compatibility with previous releases, the eIMTA introduces the concept of reference subframe configurations. The DL reference configuration is downlink-heavy, such as configuration number 5, and UL reference configuration is uplink-heavy, such as configuration number 0. These are sent to the UE using dedicated signaling

and SIB1 messages. The actual scheduling configuration is combined from these reference configurations. The scheduled subframe can be dynamically chosen between these two reference configurations, allowing very fast dynamic subframe changes. UEs that are not eIMTA compatible will only be able to use the UL reference configuration [14]. This can lead to inefficient resource use if most of the UEs do not support the eIMTA.

### 2.1.3 Additional methods described in technology report 36.828

The minimum time scale of consecutive configuration changes of the approach described in Section 2.1.1 is 640 ms. It is a relatively long time period for a modern communication system, and thus technical report (TR) 36.828 discusses three additional approaches that would enable shorter reconfiguration timescales. A shorter configuration time can provide better adaptivity for traffic variations.

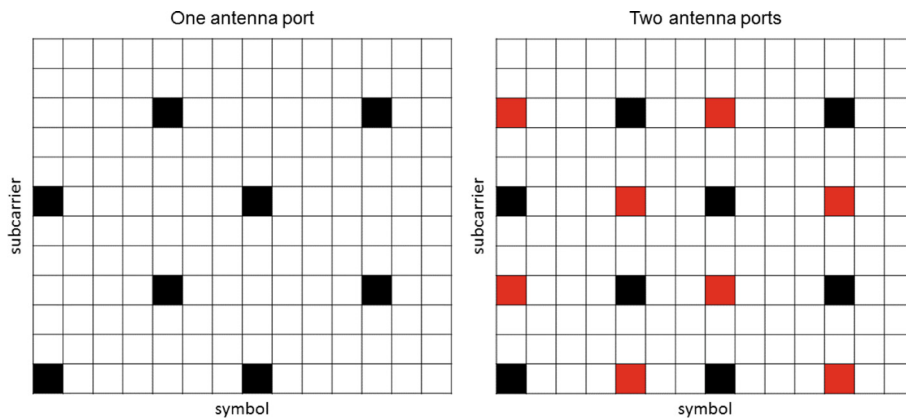
The methods described in [15] rely on explicit signaling. The signaling could be on radio resource control (RRC) level, meaning that the timescale could be in the 200-ms range. At media access control (MAC) level, the time scale can be shortened to tens of milliseconds, but it lacks error recovery support. The signaling could also be done directly on the physical layer. The physical layer signaling could cooperate with channel state information measurements and interference mitigation schemes.

None of the methods described in TR 36.828 are applicable for legacy UEs, e.g., Release 8 devices. Furthermore, the methods have a number of other open issues such as how to schedule the HARQ timeline during the change process [15]. They are also not adopted to the existing standard. We propose and analyze the dynamic TDD changing method that does not require changes to the LTE specification and operates in the scope of the LTE specification.

## 3 Downlink reference signal interference

Downlink RS interference is often neglected or forgotten when analyzing dynamic TDD in LTE. The RS is used mainly for channel estimation. In real life, we cannot always expect a full buffer-type of traffic. However, in LTE DL, the RSs are always transmitted despite the existence of data. The resource elements (REs) reserved for RS depend on the cell ID number and the transmit antenna. A DL resource block with RS is shown in Fig. 1. If multiple transmit antennas are used, the REs reserved for other antennas' RS are left empty.

Understanding the actual effect of RS interference is important. In a single antenna case, the RS occupies eight REs in each LTE DL resource block. When a normal cyclic prefix is used, the RS takes 4.76% of all the REs. Since the RS covers only some of REs, it is not obvious how



**Fig. 1** Reference signal locations in downlink LTE resource block. If multiple antennas are used, different antenna ports send RS in different resource elements (black/red)

interference impacts on the end-to-end performance. In the analysis, we used a TD-LTE software radio platform developed at Aalto University [2] to measure this impact.

The platform enables modification of the standard LTE physical layer operation, making it possible to collect system performance data inside the LTE stack. The measurement setup is shown in Fig. 2. All the nodes are synchronized and operating in TDD fashion. One node is operating as the UE and sending UL subframes with data on the physical uplink shared channel (PUSCH). The measurement node is acting as an eNodeB and the other nodes are synchronized to it. The measurement node is receiving the UE’s data and computes the SINR by comparing the received symbols to the actual transmitted symbols. The interference node is operating as a neighboring eNodeB that transmits DL subframes which overlap with the UL subframes. Half of these DL subframes contain data symbols on the physical downlink shared channel (PDSCH) and reference signal, and the other half contain only the reference signal.

The measurement results are shown in Fig. 3. The measurements were completed with about a 20-dB UL SNR level. Black lines indicate the measured values, the solid line is the UL SINR without any interference, the dotted lines presents the measured, and estimated UL SINRs in the presence of DL RS interference. The dashed lines show the UL SINR when DL interference includes both data

and RS. The horizontal axis presents the difference in the measured and interference signal power densities.

Measurements clearly indicate that the system has three distinct interference states: (i) no interference, (ii) interference from RS signal solely, and (iii) interference from the data and RS signal.

In order to consider these states in system level studies, we propose modifying the conventional signal-to-interference-plus-noise ratio (SINR) formula to take into account the RS characteristics

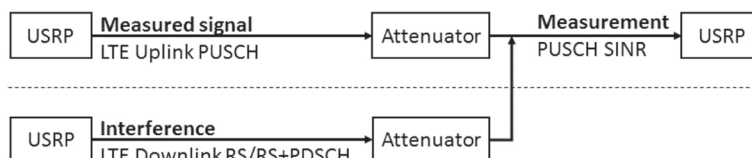
$$SINR = \frac{P}{\sum_{i=1}^n \rho_i I_i + \sigma^2}, \tag{1}$$

where  $P$  is the signal power,  $I_i$  is the signal power of the  $i$ th interfering transmitter, and  $\rho_i$  is the coefficient which depends on the interference type. If only RS is present as interference,  $\rho_i$  is 0.0476, since RS occupies 4.76 % of the resource elements. If data is also transmitted,  $\rho_i$  is 1.0.

In Fig. 3, the red lines show the estimated values from Eq. 1. It can be observed that the estimated model follows the measurements well; and therefore, this model can be used in system level analysis.

#### 4 System level interference analysis

In this section, we investigate how the actual interference modeled with Eq. 1 impacts on the system level performance. We consider an indoor office test environment



**Fig. 2** Interference measurement setup

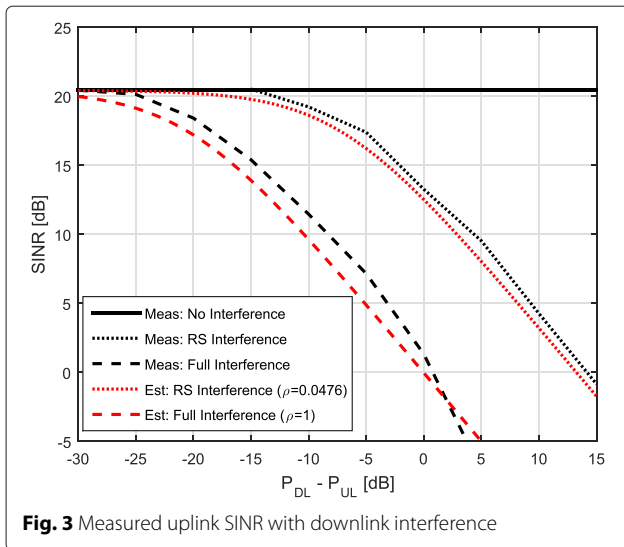


Fig. 3 Measured uplink SINR with downlink interference

Table 2 Main simulation parameters

Parameter	Value
Layout	Indoor office scenario [16]
Number of floors	3
eNodeB locations	Fixed, 20 per floor
UE locations	Randomly dropped, 20 per floor
eNodeB Tx power	20 dBm
UE Tx power	20 dBm
Number of antennas	1
Antenna gains	0 dB
Noise level	-90 dBm
Carrier frequency	2.1 GHz
Link activity probability	0.1-1.0
Simulation type	Snapshot; 10,000 repeats

deployment model proposed by ETSI and described in [16]. An office building with three identical floors is covered with LTE femtocells, 20 eNodeBs per floor. The floor plan and eNodeB locations can be seen in Fig. 4. On each floor, 20 UEs are randomly placed and each of them is connected to the eNodeB with the strongest signal. One eNodeB can be connected to a single UE. The activity describes the probability that the link is active. Inactive eNodeBs transmit downlink RSs, and active eNodeBs transmit a full buffer-type of traffic. The main simulation parameters are listed in Table 2.

Figure 5 presents the SINR CDFs for activity levels 0.1, 0.5, and 0.9. The solid lines show the downlink SINR in the active links when inactive links are transmitting DL RS. The dotted lines show the same, but now inactive links have switched to the UL subframe. It can be seen that with low link activity, the switching benefits for more improvements of 10 dB to the SINR are possible. However, with high link activity, the gain is small as can be expected.

Figure 6 shows the median SINRs with respect to the activity. If less than 30 % of the links are active, the median SINR can be improved at least 2 dB. Low link activities can be expected in a small cell network with very few or even no users connected to each eNodeB. Assuming only ON/OFF-type links and forgetting to take RS interference into account would lead to overoptimistic system performance. One can conclude that for low activity levels, it is beneficial to reduce interference and to change the BS to use UL-heavy TDD configuration.

### 5 Configuration change mechanism

Changing the subframe configuration is a dynamic process. In this section, we analyze the system transition during the configuration change procedure. First, we present how the dynamic configuration change is carried out and analyze the delays of the process. In addition, the configuration change switching cost and the related statistics are simulated and analyzed with the TD-LTE testbed.

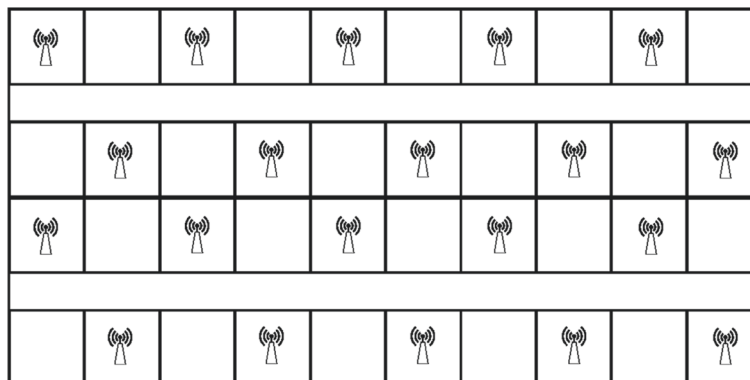
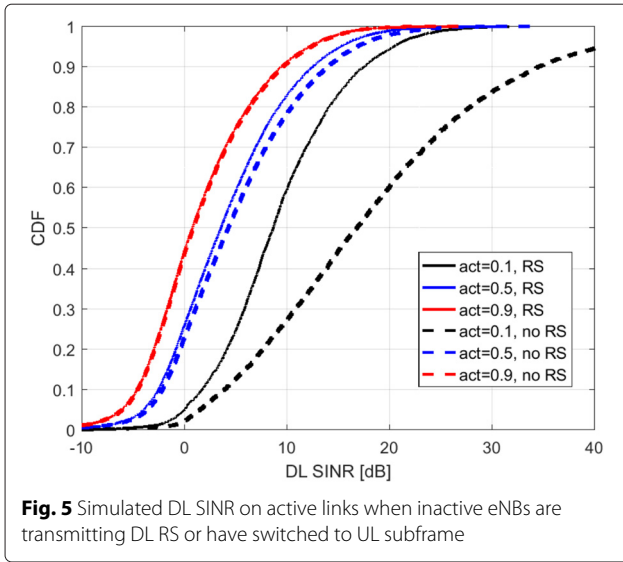
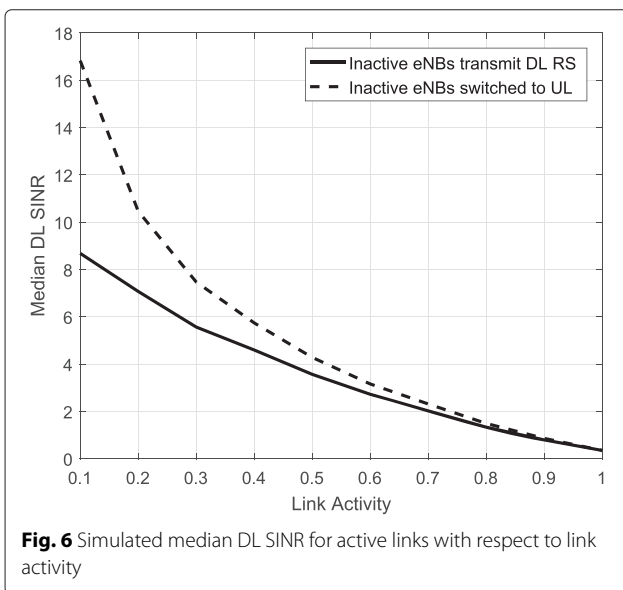


Fig. 4 Simulation building layout



### 5.1 Configuration change signaling

One of the key challenges to introduce more dynamic subframe use in TD-LTE is the handling of the HARQ processes. The reason for this is that in TD-LTE, the transmission instants of the acknowledgements and negative acknowledgements (ACK/NACK) are configuration dependent. In the new configuration, the transmission slot of the ACK/NACK of the ongoing HARQ processes may be assigned for other purposes. Hence, each HARQ process must be terminated before the system can switch the configuration. When the new configuration has been taken into use, the UE has to reattach to the network by initiating the random access (RA) procedure. The RA can be network initiated or UE initiated but completing either of them takes time.



During the termination of the HARQ processes, and before the RA procedure is finished, the network is unavailable for new traffic. In other words, no new MAC protocol data units (PDUs) are accepted for transmission. This temporarily reduces network throughput. In order to get some benefit from the subframe configuration change, the total data that the new configuration can serve should increase.

The amount of data a configuration can serve depends on the time the configuration is in use. Assume  $C_1$  and  $C_2$  are link capacities before and after a configuration change. If the configuration is not changed during time  $T$ , the initial subframe configuration could serve  $C_1 \cdot T$  amount of data. Alternatively, if the configuration is changed, the system capacity from the configuration change boundary is  $C_2(T - \Delta T)$ , where we consider that the time  $\Delta T$  is needed for changing the configuration.

In order to get some benefit from the subframe configuration change, the following condition should be fulfilled:

$$C_1 T \leq C_2(T - \Delta T) \Rightarrow 1 - \frac{C_1}{C_2} \geq \frac{\Delta T}{T}, \quad (2)$$

where we assume  $T > \Delta T$ .

#### 5.1.1 Configuration change algorithm

The performance cost of the configuration change depends mainly on two aspects: how long the HARQ processes will take to finish and the duration of the RA process.

The moment configuration change is done is called a configuration change boundary. The configuration change cannot take place before all HARQ processes have been finished. In order to guarantee that all HARQ processes are finished before the configuration change boundary, the system cannot accept new data transmission if any of the retransmission attempts would be scheduled after the change boundary. In an LTE system, one HARQ process can have four retransmission attempts, and the scheduling of the attempts is specified accurately. We propose to reduce the HARQ process finishing time by waiting for only one ACK/NACK confirmation and not to allow retransmission attempts for the HARQ process. The eNodeB sends the last packet before the configuration change boundary, stops accepting new data, and waits for one ACK/NACK that has to arrive just before the configuration change boundary. New traffic is not accepted during the ACK/NACK waiting time interval. In an LTE system, this is about 5 ms (depends on TDD configuration). The basic functionality of the aggressive approach (Algorithm A) is presented in Algorithm 1.

Using only one transmission will deteriorate link quality. However, we assume that if better link quality is expected, retransmissions are handled not by the HARQ processes

in the MAC layer but rather by the ARQ process in the RLC layer.

When configuration is changed, the user can resume the transmission only after reattaching with an RA procedure. Thus, also the time used for the RA process is considered as a configuration switching cost.

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**Algorithm 1:** Description of Algorithm A
 

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Algorithm A;

**while** *More than ACK/NACK interval to the next configuration change boundary*

**do**

    Normal operation;

**end**

**while** *Less than ACK/NACK interval to the next configuration change boundary*

**do**

    No more new PDUs from upper layers are accepted;

**end**

At the modification period boundary remove all HARQ processes;

Start new RACH procedures;

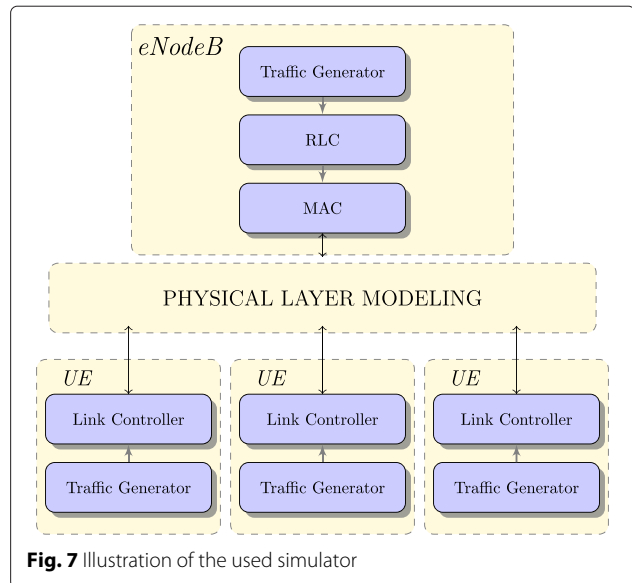
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We compare the performance of Algorithm 1 with a conventional approach (Algorithm C) where each HARQ process waits for all possible retransmissions attempts. Thus, the system reserves sufficient time to complete all transmissions. In LTE, the HARQ process can have a maximum of four retransmission attempts; and hence, it takes approximately 40 ms (four ACK/NACK interval, exact value depends on the UL/DL subframe configuration) to complete them.

## 5.2 Simulation results

### 5.2.1 Configuration change cost

To analyze the configuration change cost of the TD-LTE system, we utilize the TD-LTE testbed. The block diagram of the used simulator is shown in Fig. 7. The testbed is configured into simulator mode. The simulator mode means that we have replaced the radio hardware and radio path with an ideal connection that passes baseband samples. The UE and the eNodeB are running in the same computer as different processes. The simulator mode is essential when we want to evaluate only the higher protocol behavior and leave the physical layer effects out. In the simulation scenario, the TD-LTE network includes one eNodeB and one UE. The modification period boundary (UL/DL configuration change) is set to be executed at time moment 0. Furthermore, the throughput performance of the LTE network is calculated in the simulator cumulatively over the window of ten subframes.

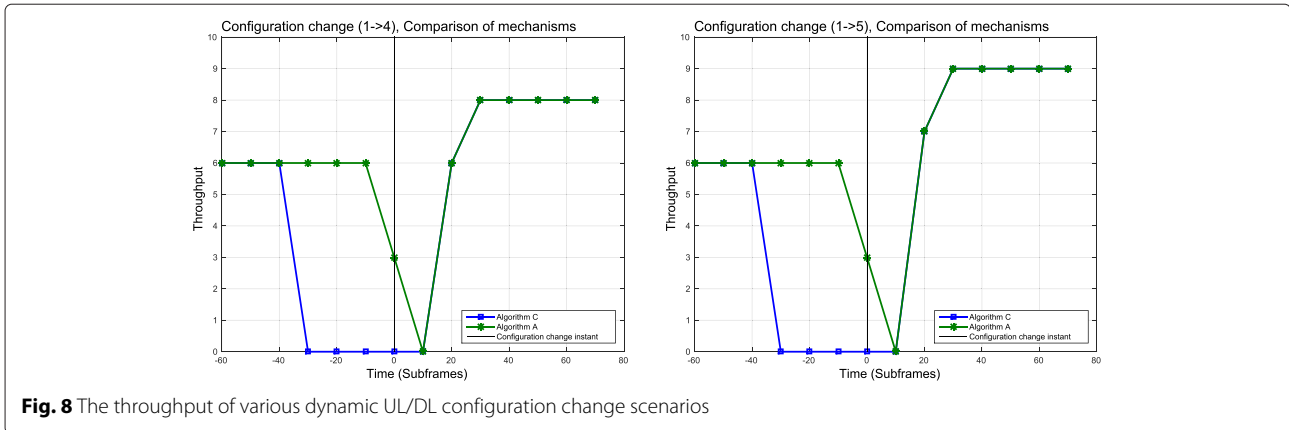


**Fig. 7** Illustration of the used simulator

Figure 8 presents the system throughput when the UL/DL configuration is changed from configuration 1 to either configuration 4 or 5. Algorithm C starts to prepare for the configuration change approximately 40 ms before the modification period boundary. After that new data is not sent to the HARQ processes, the throughput collapses to zero. In the proposed algorithm, new PDUs are accepted significantly longer, all the way until the subframe -6.

Due to the RA overhead, the first usable DL transmission slot, after the RA process, is subframe 14 for configuration 4 and subframe 13 for configuration 5. Furthermore, after the RA process, no more subframes are considered as a switching cost for the configuration change. Special subframes were considered completely as DL transmission opportunities in these simulations. After considering the full-switching overhead including the HARQ processing and RA overhead for configuration 4, the total amount of DL and UL subframes during time (subframe) period 14–600 were 469 and 116, respectively. Similar values for configuration 5 during time period 13–600 were 529 and 58, respectively.

Figure 9 presents the cumulative amount of transmitted data with and without configuration change. The results indicate that with our proposed configuration change method, the loss during the change is caught up in 60 subframes from the modification period boundary, while for Algorithm C, it takes 145 subframes. Since the configuration 5 has nine DL subframes, it reaches the cumulative transmitted DL data faster compared to the change to configuration 4. The loss of the throughput during the configuration change process is gained on with Algorithm A in 40 subframes and with the conservative method in 115 subframes. The results indicate that the benefit of



**Fig. 8** The throughput of various dynamic UL/DL configuration change scenarios

the configuration change depends on time duration  $T$ . The minimum time interval for configuration change is 640 ms.

In Table 3, we present the total amount of available UL and DL subframes if the configuration change is done. The total amount of subframes in the observed interval is 640, equal to the minimum configuration change period. In this study, we started the observation from the subframe  $-40$ . The configuration can be changed in each interval yielding the usable subframes to be from  $-40$  till 600. With Algorithm C, the last usable subframe is the subframe  $-41$ . The residual time before the configuration change boundary is in that case reserved for retransmission attempts. Since in this simulation scenario we considered ideal wireless channel conditions, these DL subframes were not utilized, and they are considered as a configuration change switching cost. For our proposed algorithm, the last usable subframe for DL transmissions was subframe  $-6$ . Thus, the switching cost for Algorithm A was significantly smaller. The UL subframes before configuration change were construed as usable until subframe  $-3$  since after that the HARQ acknowledgments would be scheduled to time instances after the configuration change boundary.

### 5.2.2 Probability of the configuration change

In order to benefit from the configuration changes, the system has to be aware of the actual traffic pattern and

amount of resources the configuration change provides. The decision problem for configuration change can be defined as follows: given the data transmission history, when it is beneficial to switch to the new configuration?

Because of the switching overhead, the new demand should last a certain time before the benefit of new UL/DL configuration compensates the switching cost. Given the data transmission time distribution  $P(t)$ , we can estimate the probability  $P(T_c + h)$  that the data transmission flow last time  $h$  given that it has lasted time  $T_c$ .

Data transmission can be described with long tail distribution, like Pareto distribution. Laurikkala [17] has shown that if a flow length is Pareto distributed, and it has lasted at least time  $T_c$ , the probability that the flow lasts  $T_c + h$  can be calculated

$$P_{11} = \left( \frac{T_c}{T_c + h} \right)^a, \tag{3}$$

where  $a$  is Pareto distribution's scaling factor.

The gain from the configuration change is achieved when the data flow is longer than the break-even time  $T$ . For a given time moment  $T_c$ , the probability of that happening is given by cumulative flow length distribution  $1 - F(T_c + T)$ , where  $F(t) = \int_{-\infty}^t P(t)$  is the cumulative distribution of the data transmission time. Similarly, the data flow can end before the break-even time  $T$  with probability  $F(T_c + T) - F(T_c)$ . As we studied in the previous paragraph, in LTE system, the time  $T$  is approximately 40–190 ms.

Configuration change is beneficial if

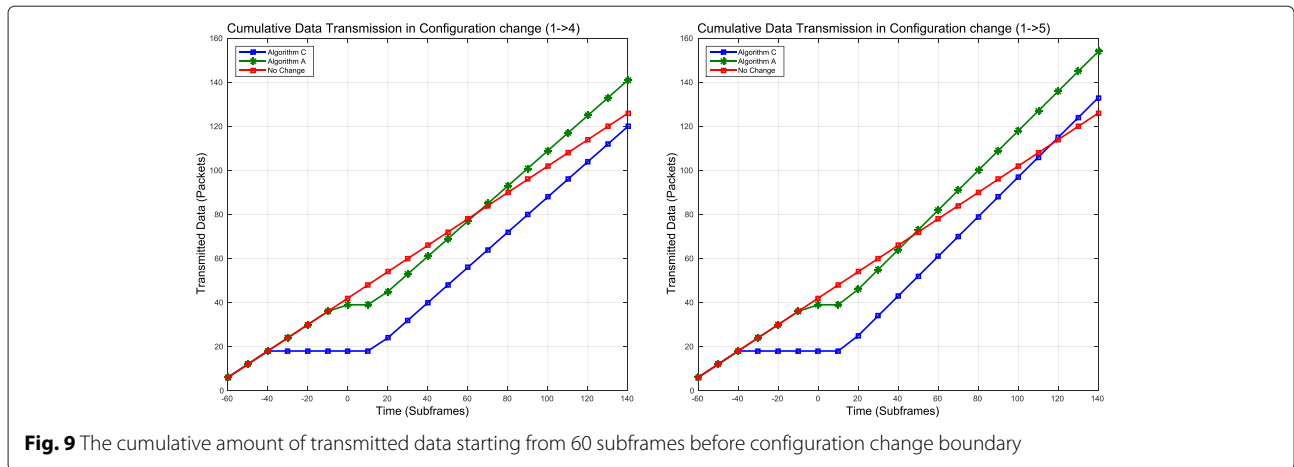
$$1 - F(T_c + T) \geq F(T_c + T) - F(T_c), \tag{4}$$

$$\psi \hat{=} \frac{1 - F(T_c + T)}{F(T_c + T) - F(T_c)} \geq 1. \tag{5}$$

**Table 3** Number of total UL and DL subframes if configuration change is performed

Configuration change	UL subframes	DL subframes	Switching cost
No change	256	384	0
1 → 4 Algorithm C	130	469	41
1 → 4 Algorithm A	130	490	20
1 → 5 Algorithm C	72	529	39
1 → 5 Algorithm A	72	550	18





**Fig. 9** The cumulative amount of transmitted data starting from 60 subframes before configuration change boundary

For Pareto distributed flow ages, this can be computed

$$\psi = \frac{1 - 1 + \left(\frac{b}{T+T_c}\right)^a}{1 - \left(\frac{b}{T+T_c}\right)^a - \left(1 - \left(\frac{b}{T}\right)^a\right)} \geq 1. \tag{6}$$

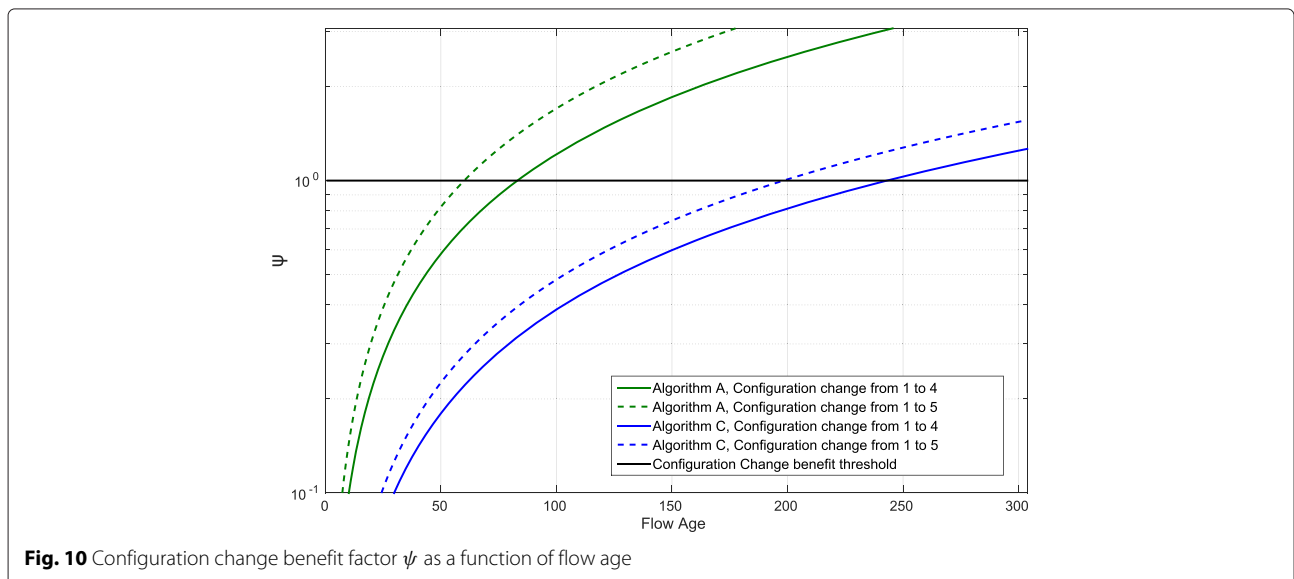
$$\psi = \frac{T^a}{(T + T_c)^a - T^a} \geq 1. \tag{7}$$

The equation describes when to change UL/DL configuration given the observed history at time moment  $T_c$  and break-even time  $T$ . Figure 10 presents this configuration change benefit factor  $\psi$  as a function of the flow age in four different configuration change scenarios. The scenarios are the same as the ones discussed in the previous paragraph. In the analysis, the used distribution shaping factor is  $a = 1.2$ , the same as used, e.g., in [17]. The results show that when the configuration is changed from

1 to 5 and Algorithm A is used, the change should be performed if the current flow age is over 50 ms. A respective value for the change from configuration 1 to 4 is approximately 60 ms. If the conservative mechanism is utilized, the flows should have lasted over 200 ms for the change from configuration 1 to 5 and 230 ms for the change from configuration 1 to 4.

### 6 Conclusions

This paper discusses the use of dynamic TDD in LTE small cells. Traffic direction in small cells is expected to vary significantly; and therefore, dynamic TDD can improve overall system performance. Additionally, in LTE system, the overall interference can be reduced by switching to uplink heavy subframe configuration. However, there is a certain switching cost for changing the used subframe configuration. In this paper, we evaluate the impact of TDD configuration on system performance at the link



**Fig. 10** Configuration change benefit factor  $\psi$  as a function of flow age

level, system level, and during dynamic subframe configuration change.

We measure the RS interference with the implemented system and match a simple interference model to the measurement data. The model is then used in system level studies. Our system level simulations show that by switching to uplink heavy subframe configuration, the performance of the system cell can be improved significantly. However, because of the limitations in LTE, the subframe configuration change cannot be done frequently and the change process causes a temporary drop in the throughput. We have evaluated and simulated the change procedure according to the LTE specification and conclude that gains can be achieved. However, the standard would be more attractive for dynamic TDD if the actual change procedure would be specifically supported. A clear time instant when the new subframe configuration is taken into use and a description of how the ongoing HARQ processes are handled at the change would make the dynamic TDD more applicable.

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#### Competing interests

The authors declare that they have no competing interests.

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