Link Adaptation Control in LTE Uplink

Pierre Bertrand
Texas Instruments Incorporated
Villeneuve-Loubet, France
Email: p-bertrand@ti.com

Jing Jiang
Texas Instruments Incorporated
Dallas, Texas, USA
Email: jing.jiang@ti.com

Anthony Ekpenyong
Texas Instruments Incorporated
Dallas, Texas, USA
Email: aekpenyong@ti.com

***Abstract*—Long Term Evolution (LTE) technology aims at addressing the increasing demand for mobile multimedia services in high user density areas. Channel aware scheduling across wide system bandwidth is one of the key techniques enabling this goal. To this end, the LTE scheduler heavily relies on an accurate and robust Link Adaptation (LA) function for predicting the best modulation and coding scheme (MCS) of a user. In this paper, we complement the popular block error rate (BLER) based LA with a scheme maximizing the throughput without BLER constraint and show that it indeed optimizes the spectral efficiency performance. We also describe a sub-optimal UL scheduler providing a good performance/complexity trade-off between a low-complexity basic scheduler and the optimal, but impractical complexity-wise.**

***Index Terms*—LTE, E-UTRAN, link adaptation, adaptive modulation and coding, scheduler, OFDM.**

I. Introduction

The Link Adaptation (LA) is a key function in wireless networks aiming at estimating the most appropriate modulation order and coding rate to be used at a given time on a radio link to meet a target criterion e.g. a block error rate (BLER). Fast Link Adaptation (FLA) was introduced as early as in CDMA and GPRS systems [4] [5] allowing for a better utilization of the instantaneous capacity as actual wireless channels are time-varying and frequency-selective, and was later extended to HSDPA systems [7] [8]. It consists in comparing every new signal over interference plus noise ratio (SINR) update of a user equipment (UE) with a number of switching thresholds that partition the locally-optimum modulation and coding schemes (MCS) along the SINR dimension to select the best MCS for that SINR. In real systems, the instantaneous SINR values undergo a feedback delay [4] (to be added to the scheduling delay), estimation errors as well as varying channel statistics such that the SINR thresholds also need to be adapted to track and mitigate these imperfections [6]- [8]. The fast MCS selection and complementary slower threshold adaptation are often referred to as Inner-Loop and Outer-Loop LA (ILLA/OLLA) respectively. LA also plays an essential role in the Long Term Evolution (LTE) wireless networks, also known as Evolved Universal Terrestrial Radio Access Network (E-UTRAN). OFDMA and SC-FDMA (single carrier FDMA) access schemes were chosen for the down-link (DL) and up-link (UL) of E-UTRAN, respectively [1]. Allocation decisions are made by the LTE scheduler on a 1 ms transmission time interval (TTI), where each decision is based, amongst other factors, on the expected instantaneous user throughput resulting from the MCS predicted by the LA function for a future TTI. Since LTE adds to WCDMA the frequency and space (MIMO) dimensions in the scheduling space, research in LA for LTE downlink has mainly focused on the associated feedback schemes ([9] [10], etc) while most basic principles of the HSDPA LA were adapted to EUTRA DL [11] [12] e.g. in applying and adapting a backoff to UEs' SINR measurements rather than adapting the MCS SINR switching thresholds. In contrast, only little focus was given to LTE UL, which differs from the DL in several aspects pertinent to LA: single-carrier access scheme, UL SINR computed by the Base Station (also referred to as eNodeB) from various UL reference signals, synchronous HARQ used with the possibility to send non-adaptive retransmissions, etc. Some preliminary performance results are provided in [13] with a simplified scheduler, ideal and instantaneous SINR knowledge of all UEs at the eNodeB.

In this paper, we extend this study to a comprehensive Frequency Domain Packet Scheduler (FDPS) running under realistic SINR measurement availability periods, and propose a solution for refreshing the UE's SINR at ILLA input optimizing the performance/complexity trade-off. In addition, we extend the conventional OLLA algorithms, all based on meeting a target BLER, to a throughput-only optimization criterion, without BLER constraint. Even though the baseline LTE duplexing mode assumed is FDD in this paper, the designs and findings can be extended to TDD as well. Similarly, a single spatial layer (SIMO) UL transmission is assumed, but the same principles would apply to transmissions involving multiple layers.

The paper is organized as follows: Section II describes two MCS mapping schemes of the ILLA with different optimization criteria: maximizing the throughput with and without a target BLER constraint. Section III describes the associated complementary OLLA algorithms. Section IV proposes an implementation option improving the performance of the baseline low-complexity MAC scheduler taking profit of some specific aspects of the LTE UL. Section V provides the system simulation setup and gives the performance of the various algorithms defined in the previous sections. Finally a conclusion is given in Section VI.

II. Inner Loop Link Adaptation

Given the SINR Γ of a user at transmission interval n and for a frequency chunk b of size N_{PRB} physical resource blocks (PRB), the ILLA estimates the optimal MCS out of a fixed MCS set that should be assigned to this user for a future transmission interval. The allocation size N_{PRB} and MCS index l provide the transport block size (TBS) [2] which directly yields (or can be used instead of) the maximum instantaneous data rate $r\left(N_{PRB}, l\right)$ currently achievable by that user on frequency chunk b. LA is driven by two different requirements, depending on the type of traffic being served:

- Time sensitive traffic: VoIP, SIP signaling, SRBs, RACH message 3, etc: LA strategy is to maximize the throughput under the constraint of not exceeding a target BLER;
- Non time sensitive traffic: non-GBR, ad-hoc users (e.g. ftp): the LA strategy is to maximize the throughput, without any BLER constraint;

A. ILLA for maximizing the throughput

We refer to this scheme as "Max Throughput". The instantaneous throughput of a UE can be approximated as:

$$\tau\left(N_{PRB}, \Gamma, l\right) \approx r\left(N_{PRB}, l\right) \times \left(1 - p_{ble}\left(N_{PRB}, \Gamma, l\right)\right) \quad (1)$$

where $p_{ble}\left(N_{PRB}, \Gamma, l\right)$ is the block error rate given UE's allocation size N_{PRB}, SINR Γ, and MCS index l. The MCS index l_{best} maximizing the throughput is therefore selected as:

$$l_{best} = \arg\max_{l} \left\{\tau\left(N_{PRB}, \Gamma, l\right)\right\} \quad (2)$$

The resulting throughput $\tau\left(N_{PRB}, \Gamma, l_{best}\right)$ can be further used to compute the UE's scheduling metric, e.g. of a proportional fair (PF) scheduler [14].

B. ILLA for maximizing the throughput under a Target BLER constraint

We refer to this scheme as "Target BLER". In this case, an additional BLER threshold T_{BLER} is applied on top of the above selection rule so that Equation (1) is refined to:

$$\tau_B\left(N_{PRB}, \Gamma, l\right) = \begin{cases} 0 \;\; if \;\; p_{ble}\left(N_{PRB}, \Gamma, l\right) > T_{BLER} \\ \tau\left(N_{PRB}, \Gamma, l\right) \;\; otherwise \end{cases} \quad (3)$$

and the selection rule (2) now applies on τ_B instead of τ.

III. Outer Loop Link Adaptation

The ILLA prediction error is addressed by applying a backoff Δ_Γ to the SINR estimates Γ at the ILLA input. Δ_Γ is adapted in the outer loop at slow rate independently for each UE. To the authors' knowledge, all OLLA algorithms published so far use the HARQ results to estimate the achieved BLER and adapt the backoff accordingly. However, it does not seem justified for radio bearers whose only target is to achieve the highest throughput, regardless of the resulting BLER. Therefore similar to the ILLA, we implemented two different OLLA algorithms to address the cases with and without target BLER constraint. The same general principle is used in both cases: for each UE, a metric is averaged across a measurement interval consisting of P measurements resulting from P transmissions. Note, even though P is common to all UEs, different measurement intervals can be of different durations depending on how often the UE was scheduled. At the end of the measurement interval, Δ_Γ can be increased or decreased by a backoff step δ_{bo} (in dB) depending on the metric value. During a measurement interval, the ILLA applies the backoff value resulting from the previous measurement interval. Tuning both the measurement interval size and the backoff step allows optimizing the trade-off of the performance / convergence time of the algorithm (Section V).

A. OLLA for achieving a Target BLER

For UEs with a Target BLER constraint, the algorithm consists in measuring the achieved BLER defined as the success rate of the P initial transmissions of the UE across the measurement interval. At the end of the measurement interval, Δ_Γ is increased / decreased by δ_{bo} depending on whether the measured BLER is higher / lower than the target BLER.

B. OLLA for maximizing the throughput

For UEs with "Max Throughput" MCS mapping criterion, we measure the achieved throughput per PRB $T_{PRB}\left(n\right)$ defined as the sum of bits per PRB successfully received across the P transmissions (including re-transmissions) of the UE during the measurement interval n:

$$T_{PRB}\left(n\right) = \sum_{p=1}^{P} t_{PRB}\left(p\right) = \sum_{p=1}^{P} \frac{N_b\left(p\right)}{N_{PRB}\left(p\right)} \quad (4)$$

where $N_b(p)$ and $N_{PRB}(p)$ are the number of bits successfully decoded and the allocation size, in PRBs, at transmission p respectively. The throughput is further averaged across measurement intervals through IIR filtering:

$$\bar{T}_{PRB}\left(n\right) = \alpha \bar{T}_{PRB}\left(n-1\right) + \left(1-\alpha\right) T_{PRB}\left(n\right) \quad (5)$$

The relative throughput variation from measurement interval $n-1$ to n is then computed as:

$$\Delta\bar{T}_{PRB}\left(n\right) = \left(\bar{T}_{PRB}\left(n\right) - \bar{T}_{PRB}\left(n-1\right)\right) / \bar{T}_{PRB}\left(n-1\right) \quad (6)$$

and compared with an hysteresis threshold T_{Hyst} for potential backoff update:

$$\Delta_\Gamma\left(n+1\right) = \begin{cases} \Delta_\Gamma\left(n\right) \;\; if \left|\Delta\bar{T}_{PRB}\left(n\right)\right| \leq T_{Hyst} \\ \Delta_\Gamma\left(n\right) + \delta_{bo}\left(n+1\right) \;\; otherwise \end{cases} \quad (7)$$

where

$$\delta_{bo}\left(n+1\right) = \begin{cases} \delta_{bo}\left(n\right) \;\; if \begin{cases} \left|\Delta\bar{T}_{PRB}\left(n\right)\right| \leq T_{Hyst} \;\; or \\ \Delta\bar{T}_{PRB}\left(n\right) > \Delta\bar{T}_{PRB}\left(n-1\right) \end{cases} \\ -\delta_{bo}\left(n\right) \;\; otherwise \end{cases} \quad (8)$$

Both IIR filtering and hysteresis threshold aim at bringing stability to the algorithm and their parameters α and T_{Hyst} were optimized on top of the interval size and the backoff increment by sweeping across a wide range of values (Section V).

IV. LTE Uplink Specifics

A. SINR computation

The LTE UL SC-FDMA access scheme involves DFT precoding over M tones, where M is the UE allocation size, corresponding to an integer number N_{PRB} of PRBs of 12 tones each. The resulting effective SINR Γ_k of UE k with the LMMSE receiver is [16]:

$$\Gamma_k = \frac{\sum_{m=0}^{M-1} \frac{\gamma_k(m)}{\gamma_k(m)+1}}{M - \sum_{m=0}^{M-1} \frac{\gamma_k(m)}{\gamma_k(m)+1}} = \frac{1}{\frac{1}{M}\sum_{m=0}^{M-1} (\gamma_k(m)+1)^{-1}} - 1 \tag{9}$$

where $\gamma_k(m)$ is the SINR over the m-th tone, expressed as:

$$\gamma_k(m) = \sum_{n=1}^{N_R} \frac{|h_{k,n}(m)|^2}{\sigma_n^2(m)} \tag{10}$$

where $h_{k,n}$ is the vector component associated to antenna n of the channel $\mathbf{h}_k(m)$, $\sigma_n^2(m)$ is the variance that appears on the diagonal of the AWGN plus out-of-cell interference covariance matrix $\mathbf{R}(m)$, and N_R is the number of receive antennas.

In this paper, we assume the Recursive Maximum Expansion (RME) scheduler [18], well suited for the SC-FDMA access scheme, where different winners can have different allocation sizes, depending on the shape of the scheduling metric envelope. The envelope is computed with a small granularity (*scheduling unit* or *chunk*) and the final averaging across allocated PRBs is only computed for the winners.

B. UL interference correlation

LTE UL implements synchronous HARQ with 8 processes (FDD and normal HARQ operation) [2]. The associated UL HARQ timing is illustrated in Figure 1, where T_P is the UE-eNB propagation delay. $T_{eNB-PUSCH}$ and T_{UE} are the maximum latencies for the eNB to decode the PUSCH and prepare the associated ACK/NACK and for the UE to decode an UL grant (and/or an ACK/NACK) and prepare the UL transmission accordingly. As can be observed, accounting for realistic processing time for constructing the physical downlink channels, the UL scheduler should make its decisions no later than on sub-frames 2-3, with freshest UL SINR from sub-frames 1-2, i.e. 7-8 sub-frames prior UL transmission in sub-frame 8.

A specific feature of LTE UL is the possibility to use non-adaptive HARQ retransmissions, where the UE re-uses the same allocation and MCS to retransmit a MAC PDU upon receiving NACK on the PHICH. This reduces DL control overhead by not transmitting an associated UL grant in conjunction with the ACK/NACK signal. In addition it creates, for a cell whose neighbors all use non-adaptive retransmission, a significant level of correlation on the received interference across 8 sub-frames, since a fraction of UL transmissions will actually be re-transmissions. This is illustrated in Figure 2 plotting the time correlation coefficient of the received interference power

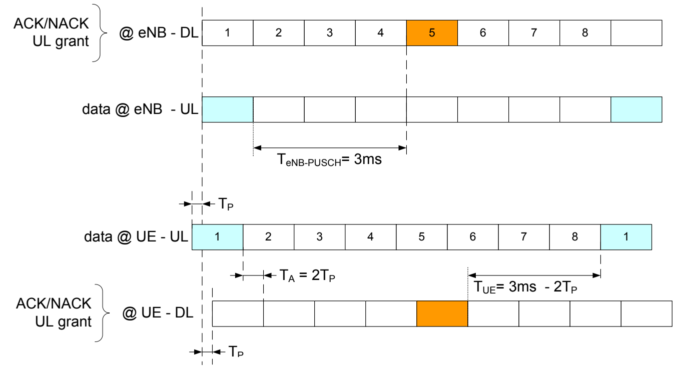

Figure 1. UL HARQ and grant timings.

per sub-carrier and per antenna σ_n^2, measured from the system simulation described in Section V. As can be observed, the correlation is as high as 60% at 8 sub-frames lag, representing up to 50% increase compared to 7 and 9 sub-frames lag.

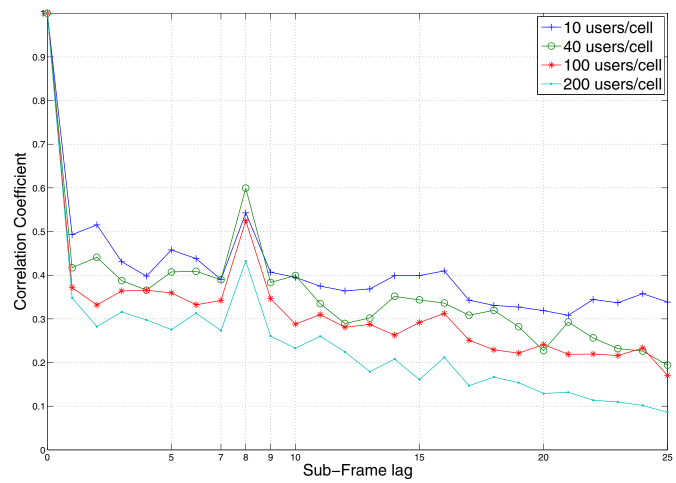

Figure 2. Correlation coefficient of the received interference σ_n^2.

C. SINR refreshing options

The per-tone channel state information (CSI) vector $\mathbf{h}_k(m)$ is estimated on the Sounding Reference Signal (SRS), for which estimation algorithms are described in [19]. The SRS is a wideband reference signal transmitted on the last SC-FDMA symbol of LTE sub-frames configured for SRS transmission, and offers a limited multiplexing capacity per SRS symbol [1] [2] so that all active users in the scheduler pool must also share this resource in time, resulting in a transmission period per UE larger than 1 ms, typically 10 ms. The noise plus interference covariance matrix $\mathbf{R}(m)$ is estimated on the Demodulation Reference Signal (DMRS) rather than the SRS, as it is more representative of the interference experienced by PUSCH data symbols, which is what scheduler cares about. As a result, the channel vector $\mathbf{h}_k(m)$ of user k is only available on sub-frames where it has a scheduled SRS. This is not the case of $\mathbf{R}(m)$, measured on every available DMRS, and which can be updated at the sub-frame rate. Therefore, if we want $\Gamma_k(b)$ to always reflect the freshest interference measurements, it should be re-computed for each user on every sub-frame. However, such high SINR refreshing rate might be impractical complexity-wise when the number of active users increases (e.g. few tens to few hundreds). This is why a low-complexity scheduler will simply use the SRS period as UE's SINR refreshing rate.

In this paper, we propose improving the low-complexity scheduler by allowing it to re-compute the SINRs of scheduled UEs only. This represents a minor complexity increase as the number of dynamically scheduled UEs per sub-frame in UL is not expected to be larger than 15-20. More specifically, we propose a 2-stage SINR computation / ILLA as follows:

1) Pre-scheduling: SINR $\Gamma_k(b)$ is computed upon every new UE's SRS instance with per-chunk granularity (Equation 9). ILLA is performed based on $\Gamma_k(b)$ to derive the optimum MCS (per (2)) and resulting instantaneous throughput $\tau_{k,b}$ which is then further re-used as is by the scheduler in subsequent sub-frames, up to the next SRS instance of that user.
2) Post-scheduling: on every sub-frame, when specifying their grants, the SINRs $\Gamma_k(B_k)$ of the scheduled users are re-computed to take into account both the size of the final allocations B_k and the interference measurement from the sub-frame preceding by 8 ms the actual transmission sub-frame, thus exploiting the correlation peak of the interference shown in Section IV-B.

Section V further compares the performance of the three implementation options.

V. Simulation results

Table I provides the main system simulation parameters. Other parameters are as specified in [3]. It should be noted that the SRS period is modeled for each UE, assuming it can send a wideband SRS spanning the PUSCH bandwidth. All sub-frames are configured for SRS transmission and all active UEs send their SRS with the same period, but possibly with a different sub-frame offset. At trial startup, the UEs' SRS offsets are distributed randomly and uniformly across all possible offsets.

Parameter	**Value or range**
Numerology	10 MHz (40 PRBs for PUSCH))
Test case	3GPP Case 1 [3]
Cell Layout	Wrap-around with 21 cells
Simulation time	5 runs, 30s each. 5s warm-up
Active users per cell	10 - 40 - 100 - 200
Rx antennas	2
Channel model	SCM 3D Urban Macro
Channel estimation	Ideal + 1.5 dB penalty (for both decoder and scheduler / LA)
UE speed	3km/h
Equalizer	MMSE w/t MRC
Traffic model	Full buffer
Scheduling delay	8 TTIs
SRS period	10 TTIs
Power Control	FPC with P_{0_PUSCH} = -86 dBm and α_{PC} = 0.8
Scheduler	Full FDPS (no TD preselection), PF with α_{IIR} = 0.999, RME [18]
Scheduling unit size	4 PRBs
HARQ retransmissions	Non adaptive

TABLE I
System Simulation Parameters.

Adaptation metric	P	δ_{bo}	α	T_{Hyst}	Ramp-up
Target BLER	50	0.5 dB	NA	NA	4 s
Max Throughput	50	0.1 dB	0.95	20%	2 s

TABLE II
OLLA parameters optimization

A. Performance and tuning of the ILLA / OLLA algorithms

We first assessed the performance of the proposed ILLA and OLLA algorithms when addressing the "Target BLER" and "Max Throughput" adaptation metrics. In these simulations, we assumed the optimum case where the SINR of each UE is refreshed on every sub-frame with the interference experienced in this sub-frame, and 40 active UEs per cell. Table II shows the results of the OLLA parameters optimization process. The OLLA ramp-up time is the observed time it takes for an SINR backoff set to 0 dB to reach steady state.

Table III shows the achieved BLER performance for various BLER targets, measured as the average success rate of 1st transmissions across all UEs, with and without the OLLA. As can be observed the OLLA is crucial for meeting the target BLERs, even at high target BLER.

Figure 3 compares the spectral efficiency performance of both "Target BLER" for various targets and "Max Throughput" schemes, where the cell-edge (5% throughput) and cell average performances are mapped onto the x and y axis respectively. As expected, the highest cell average spectral efficiency is always achieved by the "Max Throughput" scheme across the users' configurations. The "Target BLER" scheme reaches an optimum spectral efficiency performance at 20% target BLER, close to the "Max Throughput" performance. However, given this scheme does not optimize for throughput, this value is expected to vary when the cell configuration changes (e.g. the inter-cell site distance, etc), while the "Max Throughput" scheme is designed to guarantee an optimal performance for any scenario.

Moreover, Table IV shows that the average BLER observed when running the "Max Throughput" scheme is in the range of 26-28%, although the spectral efficiency performance of the "Target BLER" around these targets is weaker than e.g. at 20% target. This shows again that both algorithms aim at optimizing one performance, BLER or Throughput, but fail to jointly optimize both.

B. Performance of the SINR refreshing options

We now compare the performance of the three SINR refreshing options discussed in Section IV-C, associated with

Target BLER	**10%**	**20%**	**30%**	**35%**
Achieved BLER w/t OLLA disabled	37.3%	37.3%	37.1%	37.5%
Achieved BLER w/t OLLA enabled	13.1%	22.5%	30.2%	35.9%

TABLE III
Performance of the "Target BLER" adaptation metric

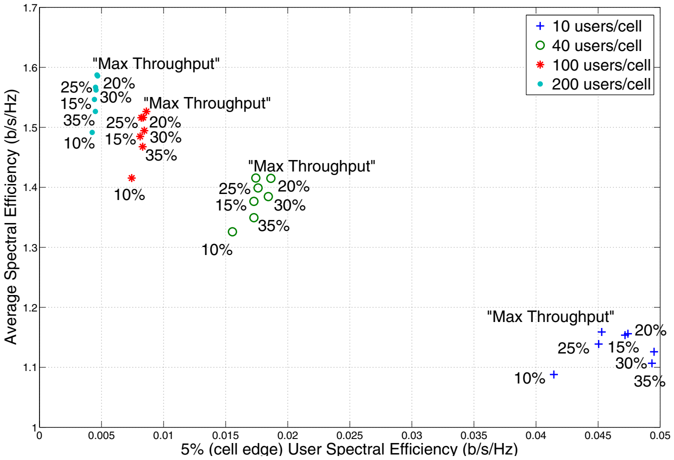

Figure 3. Spectral efficiency performance of the various LA schemes.

Number of active users	10%	40%	100%	100%
Achieved BLER	26.4%	27%	27.4%	28.3%

TABLE IV
ACHIEVED BLER WITH "MAX THROUGHPUT" SCHEME

different implementation complexities.

Figure 4 plots the achieved performance of the three implementation options, where "Max Throughput" was used as MCS mapping scheme. It shows that the proposed method, with a slight complexity increase, allows filling close to half the performance gap between the low complexity scheduler and the optimal scheduler. As a side note, both Figure 3 and Figure 4 illustrate the spectral efficiency gain from user diversity when increasing the number of users.

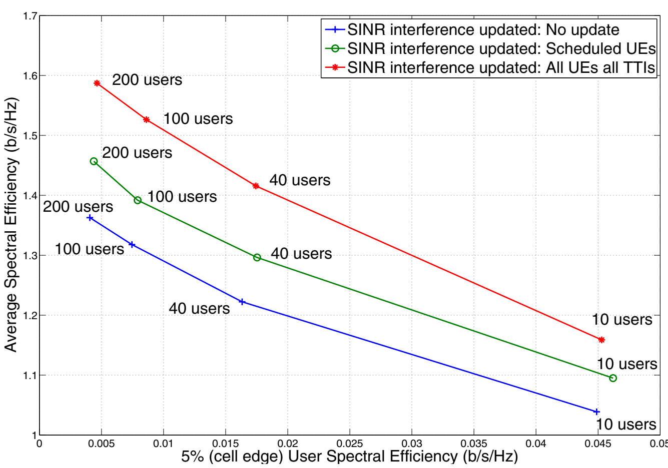

Figure 4. Spectral efficiency performance for the SINR updating options.

VI. CONCLUSIONS

This paper provides detailed design of the LTE UL Link Adaptation function. In particular, it proposes a new approach for adapting the SINR backoff in the OLLA when serving non time sensitive radio bearers without target BLER constraint. The proposed scheme is shown to outperform other schemes in terms of spectral efficiency performance. A sub-optimal scheduler is also proposed where the SINR measurements at the ILLA input are updated on each TTI for the UEs scheduled in that sub-frame for future UL transmission with a fresher interference measurement from the sub-frame preceding by 8 ms the actual transmission sub-frame, thus exploiting the correlation peak of the interference resulting from HARQ retransmissions shown in Section IV-B. This is shown to improve, with minor complexity increase, the spectral efficiency performance of a low-complexity baseline scheduler only based on SINR updates at SRS rate, and it obviates the need for the implementation of the optimal, but impractical, scheduler.

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