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Resource Allocation for Multi-User OFDMA-Based Wireless Cellular Networks

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1. Introduction

Modern wideband communication systems present a very challenging multi-user communication problem: many users in the same geographic area will require high on-demand data rates in a finite bandwidth with a variety of heterogeneous services such as voice (VoIP), video, gaming, web browsing and others. Emerging broadband wireless systems such as WiMAX and 3GPP/LTE employ Orthogonal Frequency Division Multiple Access (OFDMA) as the basic multiple access scheme. Indeed, OFDMA is a flexible multiple access technique that can accommodate many users with widely varying applications, data rates, and Quality of Service (QoS) requirements. Because the multiple access is performed in the digital domain (before the IFFT operation), dynamic and efficient bandwidth allocation is possible. Therefore, this additional scheduling flexibility helps to best serve the user population. Diversity is a key source of performance gain in OFDMA systems. In particular, OFDMA exploits multiuser diversity amongst the different users, frequency diversity across the sub-carriers, and time diversity by allowing latency. One important observation is that these sources of diversity will generally compete with each other. Therefore, efficient and robust allocation of resources among multiple heterogeneous data users sharing the same resources over a wireless channel is a challenging problem to solve.

The scientific content of this chapter is based on some innovative results presented recently in two conference papers (Calvanese Strinati et al., VTC 2009)(Calvanese Strinati et al., WCNC 2009).

The goals of this chapter are for the reader to have a basic understanding of resource allocation problem in OFDMA-based systems and, to have an in-depth insight of the state-of-the-art research on that subject. Eventually, the chapter will present what we have done to improve the performance of currently proposed resource allocation algorithms, comparing performance of our approaches with state-of-the-art ones. A critical discussion on advantages and weaknesses of the proposed approaches, including future research axes, will conclude the chapter.

2. Basic principles of resource allocation for OFDMA-based wireless cellular networks

The core topic investigated in this chapter is the performance improvement of Resource Allocation for Multi-User OFDMA-based wireless cellular networks. In this section we present the basic principles of resource allocation for multiple users to efficiently share the limited resources in OFDMA-based wireless mobile communication systems while meeting the QoS constraints. In OFDMA-based wireless cellular networks the resource allocation process is split in three families of allocation mechanisms: *priority scheduling*, *frequency scheduling* and *retransmission scheduling* techniques. While the merging of those two first scheduling mechanisms is a well investigated subject and it is called Time/Frequency dependent packet scheduling (TFDPS), smart design of re-schedulers present still some challenging open issues. TFDPS scheduling techniques are designed to enable the scheduler to exploit both time and frequency diversity across the set of time slots and sub-carriers offered by OFDMA technology. To this end, in order to fully exploit multi-user diversity in OFDMA systems, frequency scheduling algorithms besides try to select the momentary best set of sub-carriers for each user aiming at optimizing a overall criterion. In real commercial communication systems such as WiMAX and 3GPP/LTE, the frequency scheduler allocates chunks of sub-carriers rather than individual sub-carriers. The advantage of such chunk allocation is twofold: first, the allocation algorithm complexity is notably reduced; second, the signalling information required is shorten. In the literature several TFDPS scheduling algorithms have been proposed. The general scope of such scheduling algorithms is to grant access to resources to a subset of users which at a given scheduling moment positively satisfy a given cost function. Some algorithms were designed for OFDMA based systems to profit of the multi-user diversity of a wireless system and attempt to instantaneously achieve an objective (such as the total sum throughput, maximum throughput fairness, or pre-set proportional rates for each user) regardless to QoS constraints of the active users in the system. On the other hand, some scheduling algorithms were designed to support specific QoS constraints, either taking into account channel state information or not. Alternatively, one could attempt to maximize the scheduler objective (such as maximization of the overall system throughput, and/or fairness among users) over a time window, which provides significant additional flexibility to the scheduling algorithms. In this case, in addition to throughput and fairness, a third element enters the tradeoff, which is latency. In an extreme case of latency tolerance, the scheduler could simply just wait for the user to get close to the base station before transmitting. Since latencies even on the order of seconds are generally unacceptable, recent scheduling algorithms that balance latency and throughput and achieve some degree of fairness have been investigated. In (Ryu et al., 2005), urgency and efficient based packet scheduling (UEPS) was proposed to support both RT (Real Time) and NRT (Non Real Time) traffics, trying to provide throughput maximization for NRT traffic and meeting QoS constraints for RT traffics. However, UEPS bases its scheduling rule on a set of utility functions which depend on the traffic type characteristics and the specific momentary set of active users in the network. The correct choice of these utility functions have a strong impacts on the effectiveness of the UEPS algorithm. In (Yuen et al., 2007), a packet discard policy for real-time traffic only (CAPEL) was proposed. This paper stresses the issue of varying transmission delay and proposes to sacrifice some packets that have small probability to be successfully delivered and save the system resources for more useful packets. Again in section 4, we will present and comment some of the most known priority scheduling algorithms in the specific context of OFDMA-based wireless cellular networks, while our proposal will be extensively described in section 5.

Nevertheless, even with well designed TFDPS schedulers, the resource allocation process has to deal with error at destination. As a consequence, additional resource has to be allocated for accidental occurrences of request of retransmission. Nowadays, smart design of re-schedulers is still an open issue. A re-scheduler copes with negative acknowledge (NACK) packets

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which can be quite frequent in mobile wireless communications. Therefore, a re-scheduler must reallocate resources for NACK packets in a efficient and robust manner. Efficient, since it might reduce the average number of retransmission associated to NACK packets. Robust re-scheduling, in the way of minimizing the residual PER (PER_{res}). Thus, adaptive mechanisms such as Adaptive Modulation and Coding (AMC) can achieve a target PER_{res} with less stringent physical layer requirement, but with higher throughput, power saving, latency improvement and reduction of MAC signalling. In section 4, we will present and comment the most known retransmission scheduling algorithms while our proposal will be extensively described in section 5.

3. System model

The system model is mainly based on the 3GPP/LTE downlink specifications (TR25.814, 2006)(TS36.211, 2007), where both components of the cellular wireless network, i.e. base stations (BS) and mobile terminals (UE), implement an OFDMA air interface. Using the terminology defined in (TSG-RAN1#48, 2007), OFDM symbols are organized into a number of physical resource blocks (PRB or chunk) consisting of 12 contiguous sub-carriers for 7 consecutive OFDM symbols (one slot). Each user is allocated one or several chunks in two consecutive slots, i.e. the time transmission interval (TTI) or sub-frame is equal to two slots and its duration is 1ms. With a bandwidth of 10MHz, this leads to 50 chunks available for data transmission. The network has 19 hexagonal three-sectored cells where each BS transmits continuously and with maximum power. We mimic the traffic of the central cell, while others BSs are used for down-link interference generation only. Fast fading is generated using a Jakes model for modeling a 6-tap delay line based on the Typical Urban scenario (TSG-RAN1#48, 2007), with a mobile speed equal to 3km/h. Flat fading is assumed for the neighboring cells. A link-to-system (L2S) interface is used in order to accurately model the physical layer at the system level. This L2S interface is based on EESM (Effective Exponential SINR Mapping) as proposed in (Brueninghaus et al., 2005).

In the central cell, the BS has a multiuser packet scheduler which determines the resource allocations, AMC (Adaptive Modulation and Coding) parameters and Hybrid Automatic Repeat reQuest (HARQ) policy within the next slot. While the scheduler sends downlink control messages that specify the resource allocation and the link adaptation parameters adopted in the next time slot, UEs send positive or negative acknowledgment (ACK/NACK) to inform the scheduler of correct/incorrect decoding of the received data. Perfect channel state information (CSI) is assumed for all links. Nevertheless, a feedback delay is introduced between the time when CSI is available at the destination and the time when the packet scheduler performs the resource allocation.

In this model the possible presence of mixed traffic flows which present different and competing Quality of Service (QoS) requirements is studied. Two traffic classes are considered: real-time traffic (RT) and non real-time traffic (NRT). As RT traffic, we consider Voice over IP traffic (VoIP) which is modeled according to (TSG-RAN1#48, 2007). This is equivalent to a 2-state voice activity model with a source rate of 12.2kbps, an encoder frame length of 20ms and a total voice payload on air interface of 40 bytes. For RT traffic, we also consider near real-time video source (NRTV), which we model according to (TR25.892, 2004) as a source video with rate of 64 kbps and a deterministic inter-arrival time between the beginning of each frame equal to 100ms. The mean and maximum packet sizes are respectively equal to 50 and 250 bytes. As NRT traffic we consider an HyperText Transfer Protocol (HTTP), as specified in (TR25.892, 2004), that is divided into ON/OFF periods representing respectively web-page downloads and the intermediate reading times. More details on the adopted system model are summarized on table 1.

Parameter	Value
Network	
Carrier frequency	2.0 GHz
Bandwidth	10 MHz
Inter-site distance	500 m
Minimum distance	35 m
TTI duration	1 ms
Cell layout	Hexagonal grid, 19 three-sectored cells
Link to System interface	EESM
Traffic model	VoIP, NRTV, HTTP
Nb of antennas (Tx, Rx)	(1,1)
Access Technique	OFDMA
Total Number of sub-carriers	600
Nb of sub-carriers per chunk (PRB)	12
Total Nb of Chunks	50
Propagation Channel	
Parameter	Value
Fast fading	Typical urban 6-tap model, 3 km/h
Interference	White
UE	
Parameter	Value
Channel estimation	ideal
CQI reporting	ideal
Turbo decoder	max Log-MAP (8 iterations)
Dynamic Resource Allocation	
Parameter	Value
Nb of MCS	12 (from QPSK 1/3 to 64-QAM 3/4)
AMC PER_{target}	10 %
CQI report	Each TTI, with 2 ms delay
Packet Scheduling	MCI, PF, EDF, MLWDF, HYGIENE
Sub-carriers Allocation Strategy	Chunk based allocation
Number of control channels per TTI	16
HARQ	
Parameter	Value
Stop and Wait	synchronous adaptive
Number of processes	6
Retransmission Interval	6 ms
Maximum Nb of retransmissions	up to 3
Combining technique	Chase

Table 1. Main system model parameters

A limited number of control channels per TTI is considered, as the control channel capacity is always limited in realistic systems. In this study, that number, which corresponds to the maximum number of scheduled users in a TTI, is equal to 16, that is the double of the number given in (Henttonen et al., 2008) for a 3GPP/LTE system with a bandwidth of 5 MHz. For the first transmission attempt, the MCS (Modulation and Coding Scheme) selection is based on the EESM link quality metric. As suggested in the 3GPP LTE standard, AMC algorithm selects the same MCS for all chunks allocated to one UE. This solution has the advantage of make both signaling and AMC algorithm easier to be implemented on real equipment. Concerning

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adaptive HARQ, as done in (Pokhariyal et al., 2006), all the time a retransmission is scheduled, the scheduler re-computes the set of frequency chunks previously allocated to the negative acknowledged packets, depending on the re-scheduling policy.

4. Survey on resource allocation mechanisms

In this section we will focus on three main families of resource allocation techniques for packet based transmissions. The first one is related to packet scheduling algorithms that decide in which priority order resources are allocated to the different competing flows. We will consider some of the most esteemed priority schedulers, namely the maximum channel to interference ratio (MCI) (Pokhariyal et al., 2006), the proportional fair (PF) (Norlund et al., 2004), the earliest deadline first (EDF) (Chiusssi et al., 1998) and the Modified Largest Weighted Deadline First (MLWDF) (Andrews et al., 2001) schedulers. The second technique deals with frequency scheduling: the frequency dependent packet scheduler (FDPS) allocates frequency resources (hereafter chunks) to the population of users that will be served in the next transmission intervals. FDPS maps best chunks to best users, where the notion of best users depends on the priority rule of the scheduler. Any priority based selection methods such as MCI per chunk or PF per chunk selection methods (Pokhariyal et al., 2006) can be adopted. Eventually, the third technique is related to packet retransmissions and aims at deciding how chunks are allocated or reallocated to packets which require a retransmission. It could be either persistent or hyperactive methods (Pokhariyal et al., 2006), depending wether the chunk allocation for all NACK packets is kept or recomputed.
In the following, each of these techniques has a dedicated subsection to discuss in detail their limitations and advantages.

4.1 Priority scheduling

Many researchers address the problem of defining an efficient and robust resource allocation strategy for multiple heterogeneous data users sharing the same resources over a wireless channel. Priority scheduler can deal with both allocation of time and frequency resources, in order to exploit multi-user diversity in both domains. This is often referred as time/frequency domain packet scheduling (TFDPS). In this sub-section, priority scheduling is related to the time domain dimension.
Four of these well known priority scheduling algorithms are investigated in this work: max C/I (MCI) scheduler, proportional fair (PF) scheduler, Earliest Deadline First (EDF) scheduler, and Modified Largest Weighted Delay First (MLWDF) scheduler. These priority scheduling algorithms have been proposed aiming at satisfying either delay, throughput, fairness constraints of all active users or as many as possible users. While some scheduling algorithms take into account only the time constraints of the traffic flows (e.g. EDF), others take into account the momentary channel state to optimize the overall cell throughput (e.g. MCI), or, a compensation model to improve fairness among UEs (e.g. PF), or a compound of all these goals (e.g. MLWDF). The key features and drawbacks of such schedulers are the following:
MCI: Its goal is to maximize the instantaneous system throughput regardless to any traffic QoS constraints. Therefore, MCI always chooses the set of users whose momentary link quality is the highest. Even if maximum system throughput can be achieved with MCI, users whose momentary channels are not good for a relatively long period may starve and consequently release their connections. MCI is indeed inadequate for real-time traffic.
PF: Its goal is to maximize the long-term throughput of the users relative to their average

channel conditions. Thus, its goal is to trade-off fairness and capacity maximization by allocating resources to users having best instantaneous rate (over one or several chunks) relative to their mean served rate calculated using a smoothed average over an observation time window (TW_i) (Pokhariyal et al., 2006)(TSG-RAN1#44bis, 2006). While PF is a good scheduler for best effort traffic, it is less efficient for real-time traffics.

EDF: It allocates resources first to packets with smaller remaining TTLs (Time To Live) thus each packet is prioritized according to its remaining TTL (R_{TTL}). As a consequence, by serving users in order to match everyone's deadline, EDF is designed for RT traffics. The drawback of this scheduler is that multiuser diversity is not exploited since any momentary channel state information is taken into account in the scheduling rule.

MLWDF: It aims at keeping queues stable (fairness) while trying to serve users with momentary better channel conditions (throughput maximization). Contrary to EDF and MCI scheduling algorithms, MLWDF is designed to cope with mixed traffic scenarios. The major drawback of this scheduler is that its performance depends on the design of three parameters, the maximum probability for a packet to exceed TTL (for RT traffic), the requested rate (for NRT traffic) and the averaging window for rate computation. Thus correct choice of the adequate set of parameters can be system state dependent, especially in heterogenous mixed traffic scenarios.

4.2 Frequency scheduling

FDPS maps *'best'* chunks to *'best'* users. The notion of *'best'* users depends on the priority rule of the scheduler. At time i, UE k has a metric $P_{k,n}(i)$ for chunk n, which is given for instance by $P_{k,n}(i) = R_{k,n}(i)/T_k(i)$ or by $P_{k,n}(i) = R_{k,n}(i)$, respectively for PF per chunk and MCI per chunk schedulers. $R_{k,n}(i)$ is the instantaneous supportable rate for UE k at chunk n, depending on each UE's channel quality indicator (CQI) while $T_k(i)$ is the previously mean served rate. For each time i, the *'best'* UE of each chunk n is scheduled. That is the scheduled UE at chunk n is $U_n(i) = \underset{k}{\operatorname{argmax}}\, P_{k,n}(i)$.

The adoption of realistic traffic models provides different performance if compared to non realistic full buffer models. The chunk allocation process is indeed strongly influenced by the amount of data present in users' queues: with the use of non-full buffer models, resources are only allocated to users that effectively have data to send. Thus, to find the *'best'* chunk(s) for each user, several solutions may be considered. In this section, we consider two common chunk allocation algorithms whose principles are derived from (Ramachandran et al., 2008):

Matrix-based chunk allocation: it iteratively picks the *'best'* user-chunk pair in the two dimensional matrix of chunks and users. The matrix contains the metrics $P_{k,n}(i)$ of all possible user-chunk pairs.

Sequential chunk allocation: it does only the first iteration of the *matrix-based chunk allocation*. Therefore, when a user that has been selected at the first chunk-pick has not unscheduled packet in its queue, the next user with unscheduled packets in the same matrix-row will be selected. Only when the system is forced to have full-queue traffic, both chunk allocation algorithms perform the same. Otherwise, *sequential chunk allocation* may perform sub-optimally.

Note that with EDF scheduling for OFDMA based transmission, allocation is decoupled. In a first step, each packet is prioritized according to its remaining TTL (R_{TTL}) and then chunks are allocated to the ordered packets in order to maximize spectral efficiency. This approach is more efficient than the previous one, at the expense of an increase complexity at the transmitter.

4.3 Retransmissions

The *re-scheduler* allocates chunks for retransmission according to one of the common following chunk reallocation policies:

Persistent: the *re-scheduler* persists in allocating the same set of chunks previously allocated to NACK packets. The idea is to reduce both control signaling, complexity at the BS and latency. This approach used in (TSG-RAN1#Adhoc, 2007) is typically adopted for real-time traffic such as VoIP associated to small payloads.

Hyperactive: as done in (Pokhariyal et al., 2006), each time a retransmission is scheduled, the scheduler re-computes the set of *best* frequency chunks previously allocated to NACK packets.

5. Improving RRM effectiveness

As seen in section 4, TFDPS algorithms such as the maximum channel to interference ratio (MCI) per chunk or the proportional fair (PF) per chunk were designed for OFDMA based systems to profit of the multi-user diversity of a wireless system and attempt to instantaneously achieve an objective (such as the total sum throughput, maximum throughput fairness, or pre-set proportional rates for each user) regardless to QoS constraints of the active users in the system. More precisely, MCI scheduler allocates resources to users with the highest momentary instantaneous capacity; PF scheduler tries to balance the resource allocation and serve momentary good users (not necessarily the best) while providing long term throughput fairness (equal data rates amongst all users). On the other hand, some scheduling algorithms were designed to support specific QoS constraints. For instance, Earliest Deadline First (EDF) is designed to deal with real-time QoS constraints regardless to the momentary user's channel quality. Other schedulers are designed to cope with the coexistence of RT and NRT traffics (mixed traffic), as the Modified Largest Weighted Deadline First (MLWDF) algorithm. Its design objective is to maintain delay (or throughput) of each traffic smaller (or greater) that a predefined threshold value with a given probability, at the expense of an adequate set of parameters that is system state dependent.

With our first proposal, the goal is to design efficient Time/Frequency domain packet scheduling algorithms in order to maximize the overall system capacity while supporting QoS for mixed traffic flows considering either homogeneous and heterogeneous traffics. We propose to split the resource allocation process into three steps, as defined in (Calvanese Strinati et al., VTC 2009). In a first step we identify which entities (packets for RT traffics and users for NRT ones) are *rushing*. Then in step two we deal with urgencies: we allocate resources only to entities that have an high probability of missing their QoS requirements regardless to their momentary link quality. Then, if any resources (here chunks) are still unscheduled, in a third step of the proposed scheduling algorithm, we allocate resources to users with highest momentary link quality, regardless to their QoS constraints. We call the proposed algorithm *HurrY-Guided-Irrelevant-Eminent-NEeds* (HYGIENE) scheduling.

With our second proposal we tried to tackle the issue of frequency scheduling combined with retransmissions. Indeed, as pointed out in previous section, while FDPS is a well investigated subject, smart design of *re-schedulers* is still an open issue. The re-scheduler must reallocate resources for NACK packets in a efficient and robust manner.

Decoding errors are classically attributed to insufficient instantaneous signal-to-noise-ratio (SNR) level, as it is for gaussian channels. Therefore, when a packet is not correctly decoded, its retransmission is traditionally scheduled as soon as possible and on the same frequency resource until either it is successfully transmitted or retry limit is reached. Nevertheless, the mobile wireless channel is not gaussian. A more appropriate model for such channel is the non-ergodic block fading channel for which information theory helps us to define a novel approach for re-scheduling. Actually, in non-ergodic channels decoding errors are mainly caused by adverse momentary channel instance and unreliable PER predictions (Lampe et al., 2002)(Emilio Calvanese Strinati, 2005) adopted for the AMC mechanism. As a consequence, a smart *re-scheduler* should permit to forecast, given the momentary chunks instance related to the unsuccessful transmission, if correct packet decoding is impossible even after a large number of retransmissions. To this end, in our second investigation, we present a novel *re-scheduler* which exploits both information associated to a NACK as proposed in (Emilio Calvanese Strinati, 2007) (i.e. channel outage instances and CRC) to allocate the set of *'best'* suited chunks for NACK packets. In other words, we recompute the chunk allocation only if the previously selected chunks do not permit correct decoding for the selected Modulation And Coding Scheme (MCS). We call the proposed on-demand *re-scheduler* criterion as *2-bit lazy*.

5.1 Proposed HYGIENE scheduling algorithm

EDF-like schedulers do not profit of time diversity as much as they should do. MCI and PF like schedulers aiming at maximizing the cell throughput regardless of the user QoS, are totally insensitive to any time constraints of the data traffic. Based on these observations, we propose to split the resource allocation process into three steps. First a *Rushing Entity Classifier* (REC) identifies *rushing entities* that must be treated with higher priority. Depending on the nature of the traffic, entities are UEs (NRT traffic) or packets (RT). Therefore, rushing entity classification is traffic-dependent. Second the proposed scheduler deals with urgencies: we schedule the transmission of rushing entities regardless to their momentary link quality. If any resources (here chunks) are still unscheduled, in a third step, HYGIENE allocates resources to those users with better momentary link quality, regardless to their time constraints. The proposed scheduling algorithm is summarized as follows:

Step 1: The REC classifies *entities* (packets or UEs) waiting to be scheduled as *rushing* or *non-rushing*. With RT traffic, packets are classified as *rushing* if $Th_{rush} \cdot TTL + \eta \geq R_{TTL}$. Where Th_{rush} is a threshold on the QoS deadline which depends on the traffic type, η is a constant which takes into account both retransmission interval and maximum allowed number of retransmissions. With NRT traffic, UEs and not packets are classified by the REC. Therefore, the i^{th} UE (UE_i) is classified as *rushing* if it has been under-served during TW_i. More precisely, every TTI the REC checks for each UE_i if $(TW_i - t_{now,i}) \leq (QoS_i - tx_{data,i})/R_{min}$. Where $t_{now,i}$ is the elapsed time since the beginning of TW_i, QoS_i the QoS requirements of the UE class of traffic, $tx_{data,i}$ the total data transmitted by user i during $(TW_i - t_{now,i})$ and R_{min} the minimum transmission rate of the system. Note that Th_{rush}, η and TW_i are scheduler design parameters.
Step 2: Resources (chunks) are allocated to *rushing entities* with an EDF-like scheduler which allocates *best* chunk(s) to entities with higher deadline priority. Deadline priority metrics differ between RT and NRT traffics: while with RT traffic deadline priority depends on R_{TTL}, with NRT traffic it depends on the lack of data transmitted in TW_i. Again, chunks are selected in order to maximize the spectral efficiency.
Step 3: All unscheduled resources (chunks) are allocated to users which maximize the cell throughput regardless to any QoS constraints of active UEs. Thus, the allocation is done according to MCI per chunk, following the 'matrix-based chunk allocation' described previously with $P_{k,n}(i) = R_{k,n}(i)$.

5.2 Proposed 2-bit lazy frequency re-scheduling algorithm

Many delay-constrained communication systems, such as OFDM systems, can be characterized as instances of block fading channel (Ozarow et al., 1994). Since the momentary instance of the wireless channel has a finite number of states n_c the channel is non-ergodic, and it admits a null Shannon capacity (Ozarow et al., 1994). The information theoretical limit for such channels is established by defining an outage probability. The outage probability is then defined as the probability that the instantaneous mutual information for a given fading instance is smaller than the information rate R associated to the transmitted packet:

$$\mathrm{P_{out}} = \Pr(I(\gamma, \alpha) < R) \tag{1}$$

where $I(\gamma, \alpha)$ is a random variable representing the instantaneous mutual information for a given fading instance α and γ is the instantaneous SNR.

For an infinitely large block length, the outage probability is the lowest error probability that can be achieved by a channel encoder and decoder pair. Therefore, when an information outage occurs, correct packet decoding is not possible. The outage probability is an information theoretic bound on the packet error rate (PER) in block fading, and thus no system can have a PER that is better than the outage probability.

For a generic code $\mathcal{C}$, assuming Maximum Likelihood decoding, we can express the packet error probability of the code $\mathcal{C}$ as:

$$P_e^{\mathcal{C}}(\gamma) = P_{e|out}^{\mathcal{C}}(\gamma)\mathrm{P}_{\mathrm{out}}^{\mathcal{C}}(\gamma) + P_{e|\overline{out}}^{\mathcal{C}}(\gamma)(1 - \mathrm{P}_{\mathrm{out}}^{\mathcal{C}}(\gamma)) \tag{2}$$

where $P_{e|out}^{\mathcal{C}}$ and $P_{e|\overline{out}}^{\mathcal{C}}(\gamma)$ are respectively the packet error probability when transmission is in outage and when it is not. For capacity achieving codes Eq. (2) can be tightly upper bounded by:

$$P_e^{\mathcal{C}}(\gamma) \lessapprox \mathrm{P}_{\mathrm{out}}^{\mathcal{C}}(\gamma) + \underbrace{P_{e|\overline{out}}^{\mathcal{C}}(\gamma)(1 - \mathrm{P}_{\mathrm{out}}^{\mathcal{C}}(\gamma))}_{\mathrm{P}_{\mathrm{noise}}^{\mathcal{C}}(\gamma)} \tag{3}$$

Considering capacity approaching codes an analytical expression of $\mathrm{P}_{\mathrm{noise}}^{\mathcal{C}}(\gamma)$ is not trivial, but the inequality (3) still holds. We can indeed distinguish two components of the packet error probability: the code outages due to fading instance and noise respectively.

In our work we propose to exploit at the transmitter side the knowledge on both components of the PER: the code outages due to fading instance and noise respectively. As proposed in (Calvanese Strinati et al., WCNC 2009), the receiver can send a 2-bit ACK/NACK to feedback such information: one bit informs on successful/unsuccesfull decoding (CRC), the other on code outages due to fading instance. Alternatively, the classic 1-bit feedback (CRC) can be computed at the receiver and, code outages due to fading instance can be directly estimated at the transmitter side if the channel coefficients are known at the transmitter. Based on these assumptions, we propose the *2-bit lazy frequency re-scheduler*. The goal of *2-bit lazy frequency re-scheduler* is to strongly limit unsuccessful retransmissions attempts. To this end, when retransmissions are scheduled, the proposed *re-scheduler* checks both components of the packet error probability outlined by equation (3). The *2-bit lazy frequency re-scheduler* works as follows:

Step 1: When a retransmission is required (NACK on CRC), the receiver or the transmitter (depending on the system implementation) checks if decoding failure is associated to a

channel outage.
Step 2: If $I(\gamma, \alpha) < R$, transmission is in outage and *best* chunk allocation is recomputed only for $NACK_{out}$ packets.
Step 3: Otherwise, if $I(\gamma, \alpha) \geq R$, retransmission is due only to a unfavorable noise instance and the *2-bit lazy frequency re-scheduler* reallocates the same set of chunks for the packet retransmission.

To detect a channel outage it is necessary to compute the instantaneous mutual information associated to previous transmission(s) of the NACK packet. Such instantaneous mutual information can be computed as follows:

$$I(\gamma, \alpha) = \frac{1}{n_c} \sum_{i=1}^{n_c} I_i \left(\sum_{k=1}^{K} \frac{|\alpha_{i,k}|^2}{\sigma_k{}^2} \right)$$

where

$$I_i = \log_2(M) - \frac{1}{M} \sum_{k=1}^{M} E_z \left[\log_2 \left(\sum_{q=1}^{M} A_{i,k,q} \right) \right] \quad (4)$$

and $$A_{i,k,q} = \exp[-\frac{|\alpha_i a_k + z - \alpha_i a_q|^2 - |z|^2}{2\sigma^2}]$$

Note that equation (4) is derived from (Ungerboeck, 1982) where **a** is the real or complex discrete signal transmitted vector. Moreover, all information required can be directly available at the receiver: M (size of the M-QAM modulation alphabet) and R are known since the MCS is known at the receiver; both α_i and the noise variance σ^2 are known at the receiver using training pilots based channel estimation; **a** is known from the demapper. z are the Gaussian noise samples, with zero-mean and variance equal to σ^2. Mutual information is computed over the n_c sub-carriers and the K current transmissions on which the packet is transmitted.
While *hyperactive* re-scheduler recomputes chunk allocation for all NACK packets, *lazy* does it only for $NACK_{out}$ packets. Both re-schedulers can adopt any FDPS such as MCI per chunk, PF per chunk or others. Complexity added by packet outage detection is low because the mutual information can be computed easily thanks to Look-Up Tables (LUT) or polynomial expansion. Thus, the overall complexity of the proposed *lazy* re-scheduler is in between the two classical *1-bit persistent* and *1-bit hyperactive* methods.
It is possible to further improve the effectiveness of chunk re-allocation algorithms. First, banning some chunks during a given period for a sub-set of user at step 2, may prevent from repetitive errors in the chunk allocation process. Second, $NACK_{out}$ packet detection can also be based on *accumulative* mutual information of both current and future packet transmission attempts in a given set of chunks. In this case, the instantaneous mutual information is computed as in (4) except that the summation is done over K+1 transmissions, and under the assumption that $\frac{|\alpha_{i,K+1}|^2}{\sigma_{K+1}{}^2} = \frac{|\alpha_{i,K}|^2}{\sigma_K{}^2}$.

6. Numerical results

In this section the effectiveness of the two proposed approaches, HYGIENE scheduling and Lazy frequency (re)scheduling, is evaluated comparing it with the classical resource allocation techniques presented in section 4. Schedulers are compared in terms of maximum achievable cell traffic load in different traffic scenarios, considering either single traffic, mixed real-time traffic and heterogeneous mixed traffic scenarios, following the metrics defined in (TR25.814,

2006)(TSG-RAN1#48, 2007). Performance are also assessed in terms of residual Packet Error Rate (through its cumulative density function) and chunk re-allocation cost, while varying the number of maximum retransmissions $rxtx_{max}$.
Simulation results are given for the system and traffic models presented in section 3. Results are averaged over 100 independent dynamic runs, where at the beginning of each run UEs are randomly uniformly located in the central cell. Positions, bi-dimensional log-normal shadowing and path loss values are kept constant for the duration of each run. Each run simulates 100 seconds of network activity and at each TTI channel realizations are updated.

6.1 Packet scheduling

In this first subsection, we assess the effectiveness of our proposed HYGIENE scheduling algorithm comparing it to four scheduling algorithms often investigated in the literature: MCI, PF, MLWDF and EDF. For this performance evaluation, the following assumption holds: all the time a retransmission is scheduled, the scheduler re-computes the set of frequency chunks previously allocated to the negative acknowledged packets. Furthermore, for MLWDF scheduling, we adopt the same parameters as the ones suggested in (Andrews et al., 2001).
Schedulers are compared in terms of maximum achievable cell traffic load in three different traffic scenarios:

Scenario A (*single traffic* scenario): unique traffic type in the cell for all UEs.

Scenario B (*mixed real-time traffic* scenario): coexistence of VoIP and NRTV traffic in the same cell.

Scenario C (*heterogeneous mixed traffic* scenario): coexistence of VoIP and HTTP traffic in the same cell.

To evaluate the maximum achievable cell traffic load we use the metrics defined in (TR25.814, 2006)(TSG-RAN1#48, 2007). The maximum achievable cell traffic load for real-time traffics is defined as the number of users in the cell when more than 95% of the users are satisfied. VoIP and NRTV users are considered satisfied if their residual BLER is below 2% and their transfer delay is respectively below 50ms and 100ms. HTTP users are considered satisfied if their average bit rate is at least 128 Kbps.
On figure 1 we show our simulation results for VoIP, NRTV and HTTP traffics considering *scenario A*. Under single VoIP traffic, the highest system load is achieved with EDF and HYGIENE (up to 540 VoIP UEs). MCI, PF and MLWDF achieve respectively up to 445, 440, and 360 satisfied VoIP UEs. Performance gap between EDF or HYGIENE and MCI or PF is not surprising. Actually, since both PF and MCI aim at maximizing the cell throughput regardless of the user time QoS constraints, with the increasing number of real-time flows, many users may face momentary service starvation and consequently, exceed the maximum delivery delay (50 ms). This is not the case with EDF or HYGIENE since both schedulers allocate best chunk(s) to entities with higher QoS deadline priority. What can look surprising is the poorer performance of MLWDF scheduling. Classical performance evaluations for MLWDF show that MLWDF is a good scheduler with both RT and NRT traffics. However, in such studies an unlimited number of control channels per TTI is assumed. We compare performance in a more realistic scenario where the number of control channels per TTI, and thus the maximum number of scheduled users per TTI (UE/TTI), is limited to 16. Thus, we observe by simulation that such limitation has significant impact only on MLWDF capacity performance.
For single NRTV traffic, maximum cell capacity performance obtained with any of the investigated schedulers is very similar, ranging from up to 95 satisfied UEs with MLWDF

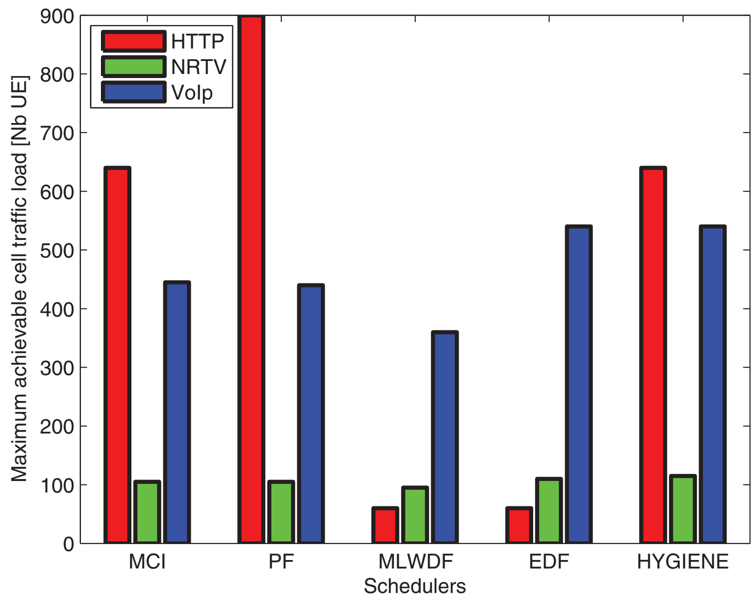

Fig. 1. Scenario A (*single traffic*): maximum achievable cell capacity with PF, MCI, MLWDF, EDF and HYGIENE schedulers.

(worst case), to up to 115 satisfied UEs with HYGIENE. With single HTTP traffic, best performance is obtained as expected with PF, having up to 900 HTTP UEs satisfied. MCI and HYGIENE perform the same (640 UEs each) while both EDF and MLWDF can satisfy very few UEs (up to 60 UEs).

On figure 2 we show our results for coexistent VoIP and NRTV traffics (*scenario B*). In our simulations we fix the number of NRTV traffic to 75 and we vary the number of VoIP. Best performance is obtained with HYGIENE, having up to 250 VoIP UEs while 75 NRTV UEs are satisfied too. Other schedulers perform as follows. EDF scheduler serves more VoIP UEs (up to 220 VoIP) than PF (up to 140 VoIP) and MLWDF (up to 70 VoIP). Worst performance is obtained with the non QoS aware MCI scheduler, having no VoIP UEs satisfied when 75 NRTV UEs are satisfied. When considering the coexistence of 75 NRTV UEs and 425 VoIP UEs, we obtained by simulation that limiting respectively to 16, 32 and 50 UE/TTI, MLWDF achieves a user satisfaction equals to 41.4%, 99.6% and 100%. In the last two cases, MLWDF performs even better than the other schedulers subject to the same restriction, except the HYGIENE one. Again, we can see that the number of control channels has significant impact on MLWDF capacity performance.

On figure 3 we mimic a heterogeneous network traffic. We fix the number of HTTP flows to 200 UEs while we evaluate the maximum VoIP UEs capacity. When scheduling is based on EDF or MLWDF ordering rules, any UE (HTTP and VoIP) can be satisfied. As expected, we observe that EDF scheduler results totaly inadequate since it cannot efficiently deal with NRT traffic. Furthermore, we observe again how MLWDF is deeply penalized by the UE/TTI limitation. Besides, MCI serves up to 180 satisfied VoIP UEs, PF up to 370 VoIP UEs. Best performance is obtained with HYGIENE scheduler, which serves up to 390 satisfied VoIP UEs. Contrarily to (*scenario A* with HTTP only), HYGIENE scheduler performs better than PF in this mixed scenario, showing the supremacy of the rushing approach. The above results were obtained with empirically optimized rushing thresholds optimized.

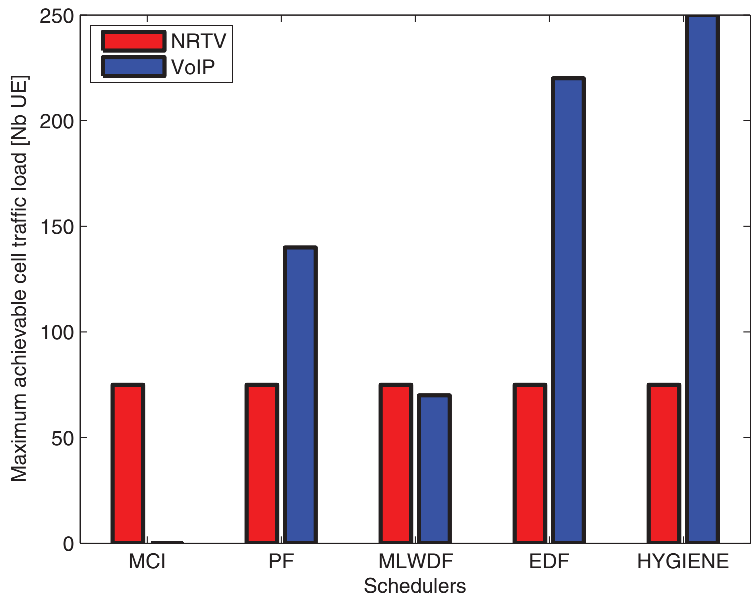

Fig. 2. Scenario B (*mixed real-time traffic*): maximum achievable cell capacity with PF, MCI, MLWDF, EDF and HYGIENE schedulers imposing 75 active NRTV flows.

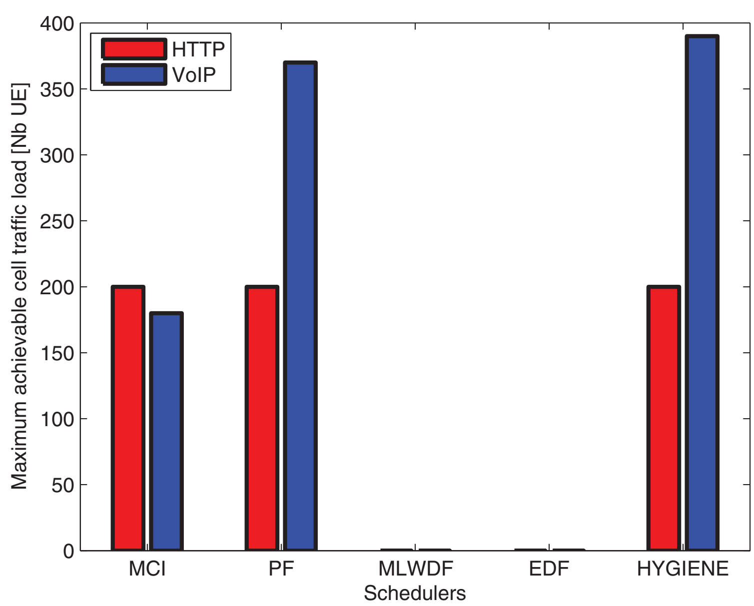

Fig. 3. Scenario C (*mixed heterogeneous traffic*): maximum achievable cell capacity with PF, MCI, MLWDF, EDF and HYGIENE schedulers imposing 200 active HTTP flows.

On figure 4 we mimic coexistent activity of 225 VoIP and 75 NRTV UEs testing different rushing thresholds for both VoIP and NRTV: $Th_{rush,VoIP}$ and $Th_{rush,NRTV}$. Our goal is to determine whether HYGIENE performance depends on an optimal combination of ($Th_{rush,VoIP}$, $Th_{rush,NRTV}$). Simulations show that a large range of ($Th_{rush,VoIP}$, $Th_{rush,NRTV}$) slightly affects user satisfaction ($Th_{rush,VoIP} \leq 40\%$ and $Th_{rush,NRTV} \leq 90\%$).

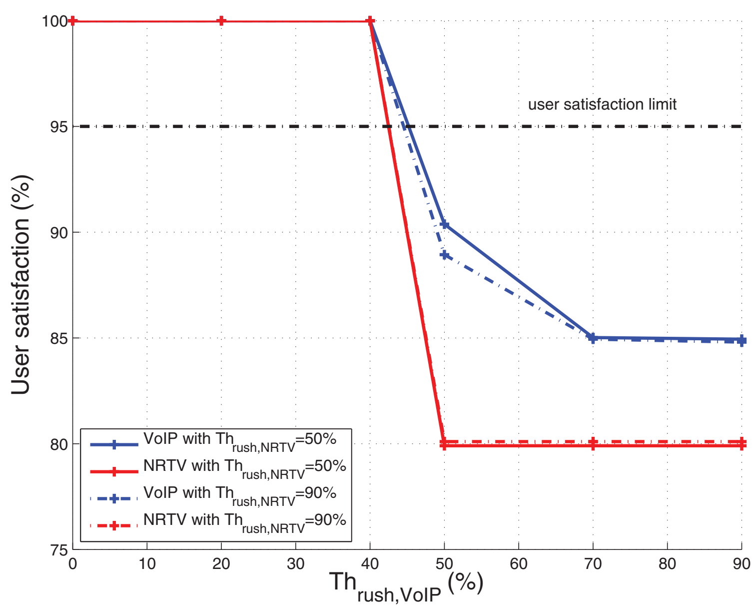

Fig. 4. Scenario B (*mixed real-time traffic*): sensitivity of HYGIENE performance on rushing threshold design.

We also looked for the quasi-optimal range of $Th_{rush,VoIP}$ and $Th_{rush,NRTV}$ in the single traffic scenario. We observed that user satisfaction for VoIP UEs is not affected if $Th_{rush,VoIP} \geq 20\%$ and, for NRTV UEs is constant for any $Th_{rush,NRTV}$ value.

6.2 Coupling of priority scheduling with multi-user re-scheduler

In this section we investigate the effectiveness of coupling a priority packet scheduler with a well designed multi-user *re-scheduler*. To this aim, we compare the performance of three classical priority packet scheduling algorithms (MCI, PF and EDF) coupled with *1-bit persistent*, *1-bit hyperactive* and *2-bit lazy* frequency *re-schedulers*. Performance is compared in terms of maximum achievable system capacity, PER_{res} cumulative density function (CDF) and chunk re-allocation cost for the system and traffic models presented in section 3. Results obtained for *1-bit persistent*, *1-bit hyperactive* and *2-bit lazy* re-schedulers are respectively plotted with orange, red and blue colors.

On figures 5, 6 and 7 we compare the pairs of priority and re-schedulers in terms of maximum achievable system capacity respectively with $rxtx_{max} = 1$ and $rxtx_{max} = 2$. To evaluate the maximum achievable cell traffic load we use the metrics defined in (TR25.814, 2006) and updated in (TSG-RAN1#48, 2007). On figure 5 we show our simulation results for VoIP traffic with $rxtx_{max} = 1$ and *matrix-based chunk allocation*. With this scheduling configuration *1-bit hyperactive* or *2-bit lazy* performs the same, outperforming *persistent* re-scheduling respectively of 120%, 135% and 150% with PF, EDF and MCI packet schedulers. Best performance is obtained coupling EDF with *1-bit hyperactive* or *2-bit lazy*, having a cell capacity of 400 UE. When using the HYGIENE scheduler (not plotted here), we observed the same conclusions: HYGIENE with *1-bit hyperactive* and *2-bit lazy* reached a cell capacity of 420 UE while HYGIENE with persistent rescheduling only achieved a cell capacity of 170 UEs. We also investigated two other scheduling scenarios when $rxtx_{max} = 1$: VoIP traffic with *sequential chunk allocation* and, NRTV traffic with both chunk allocation scheduling. We did not plot our simulation results for these scenarios because in both cases QoS constraints are not met.

On figure 6 we show our simulation results for VoIP traffic with $rxtx_{max} = 2$ and *sequential chunk allocation*. With this scheduling configuration system capacity improvement obtained with *2-bit lazy* instead of the other two re-schedulers is significant: capacity is multiplied by 2.6 even with respect to the hyperactive scheme. Again, best performance is obtained for the pair EDF and *2-bit lazy*, having the maximum system capacity of 540 UEs. *2-bit lazy* outperforms *1-bit hyperactive* when chunk allocation is sequential since in this case chunk allocation is less effective (chunk search is not exhaustive) and can even introduces additional errors. It can happen that when a retransmission is scheduled, the new pair user-chunk(s) can be associated to a higher error probability. *2-bit lazy* is more robust to such error since chunks are not reallocated when outage does not occur. On the contrary, with matrix-based chunk allocation, an exhaustive search of the *best* user-chunk(s) pair is done. As a consequence, this phenomenon disappears and *1-bit hyperactive* performs as *2-bit lazy*. Furthermore our results show how performance of non real-time QoS based schedulers (e.g. MCI) can be significantly improved with *2-bit lazy* re-scheduler.
On figure 7 we show our simulation results for NRTV traffic with $rxtx_{max} = 2$ and *matrix-based chunk allocation*. Gains between persistent and lazy retransmission schedulers are respectively equal to 5%, 6.3% and 7% with PF, EDF and MCI packet schedulers. As for the above scenarios, best performance is obtained with EDF priority scheduling, having the maximum system capacity of 120 NRTV UEs when retransmissions are rescheduled with *2-bit lazy* or *1-bit hyperactive*. Note that even when same performance is obtained with *1-bit hyperactive* and *2-bit lazy* re-schedulers, complexity is significantly reduced by *2-bit lazy* as it will be discussed later. Dealing with our HYGIENE scheduler (not plotted here), it achieves quite the same performance as the ones obtained with EDF, with a slight gain for *1-bit hyperactive* and *1-bit persistent* (cell capacity of 120 UEs instead of 117 UEs).
On figure 8 the three re-schedulers coupled with *sequential chunk allocation* are compared in terms of PER_{res} CDF for 180 VoIP traffic activity. The priority scheduler is the MCI and $rxtx_{max} = 3$. VoIP traffic QoS constraints impose a target of $PER_{res} < 0.02$ for at least 95% of users. Simulation results show how, while *1-bit persistent* re-scheduler cannot guarantee such QoS requirements, both *1-bit hyperactive* and *2-bit lazy* re-schedulers do: 95% of users have respectively a PER_{res} of $2.6 \cdot 10^{-1}$, $6 \cdot 10^{-3}$ and $2.8 \cdot 10^{-3}$. Therefore *2-bit lazy* has best performance also in terms of PER_{res} CDF.
On table 2 we compare *1-bit hyperactive* and *2-bit lazy* re-schedulers in terms of chunk re-computation ratio (η), which is the percentage of chunk re-allocation per information packet. We compute η for the three re-schedulers as follows:

Persistent: chunk re-allocation is never done, $\eta = 0$;

Hyperactive: since chunk re-allocation is done for all NACK packets, η is the ratio between the sum of all NACKs and the sum of all transmitted information packets;

Lazy outage: since chunk re-allocation is done only for $NACK_{out}$ packets, η is the ratio between the sum of $NACK_{out}$ and the sum of all transmitted information packets.

Note that re-scheduling is activated only if the number of retransmissions does not exceed $rxtx_{max}$.
Numerical results on table 2 are reported for *matrix based chunk-allocation* and $rxtx_{max} = 2$. We verify that while PER_{res} and capacity are at least not degraded (often improved, see figures 5, 6, 7 and 8) by *2-bit lazy* re-scheduling, *1-bit hyperactive* does chunk re-computation more often. For instance, coupling MCI with *1-bit hyperactive* we observe respectively for VoIP and NRTV traffics $\eta = 7.3\%$ and $\eta = 9.5\%$. Coupling MCI with *2-bit lazy*, the re-computation ratio is

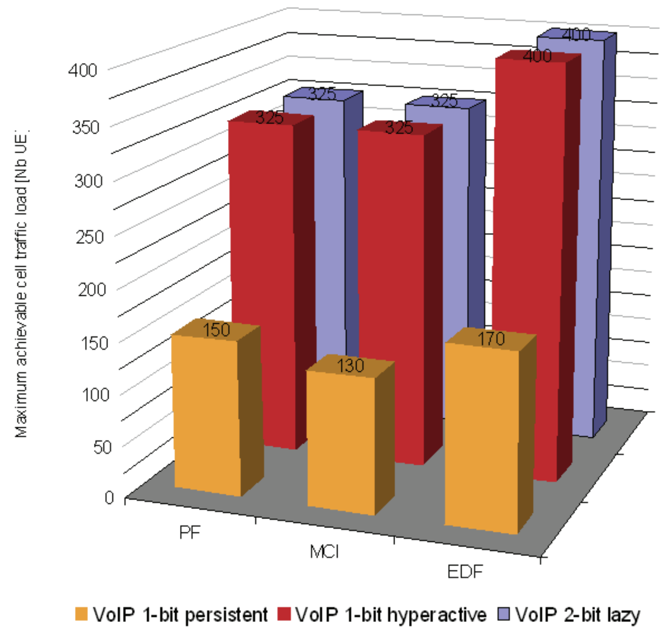

Fig. 5. $\mathbf{rxtx_{max}} = \mathbf{1}$: VoIP traffic. Comparison of 1-bit persistent, 1-bit hyperactive and 2-bit lazy frequency *re-schedulers* coupled with PF, MCI and EDF schedulers plus matrix-based chunk allocation

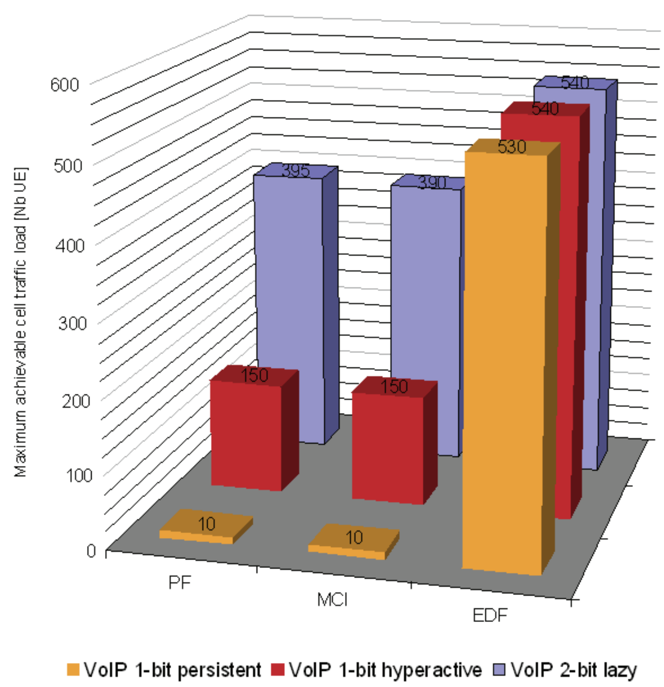

Fig. 6. $\mathbf{rxtx_{max}} = \mathbf{2}$: VoIP traffic. Comparison of 1-bit persistent, 1-bit hyperactive and 2-bit lazy frequency *re-schedulers* coupled with PF, MCI and EDF schedulers plus sequential chunk allocation

approximately divided by 10 for VoIP and by 5 for NRTV traffics. Indeed, *2-bit lazy* permits to notably reduce chunk re-allocation costs since it recomputes chunk allocation merely for $NACK_{out}$ packets. Comparing *2-bit lazy* with *1-bit persistent*, which is a very low complexity

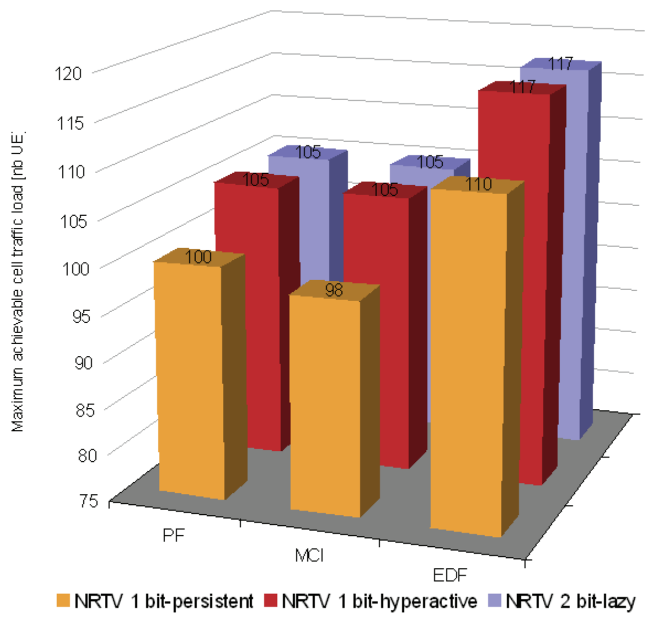

Fig. 7. $\mathbf{rxtx_{max}} = \mathbf{2}$: NRTV traffic. Comparison of 1-bit persistent, 1-bit hyperactive and 2-bit lazy frequency *re-schedulers* coupled with PF, MCI and EDF schedulers plus matrix-based chunk allocation

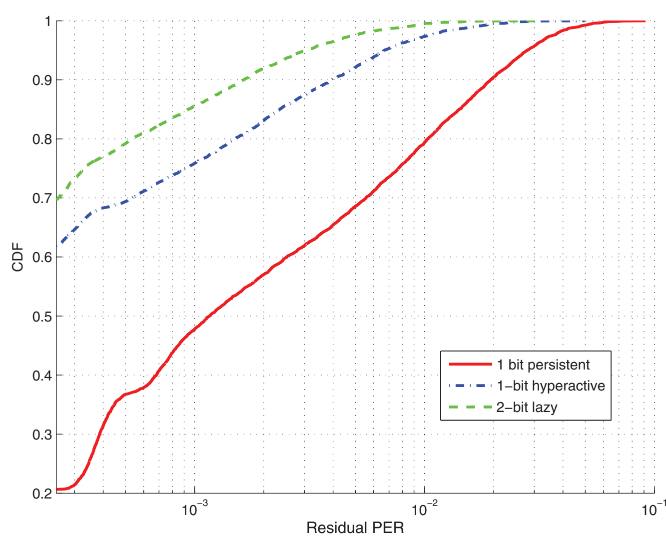

Fig. 8. $\mathbf{rxtx_{max}} = \mathbf{3}$: VoIP traffic. CDF of the residual PER for 180 UE/sector. Comparison of 1-bit persistent, 1-bit hyperactive and 2-bit lazy frequency *re-schedulers* coupled with MCI scheduler and sequential chunk allocation

chunk allocation re-scheduler, *2-bit lazy* notably performs best in terms of both maximum achievable system capacity and PER_{res} at the expense of very small additional complexity cost.

Chunk re-computation ratio can be further reduced by 4 when $NACK_{out}$ detection is based on *accumulative* mutual information as suggested at the end of section 5. For the same simulation scenario of table 2, the re-computation ratio is 0.12% for (MCI, VoIP) and 0.98% for (EDF, NRTV).

Scheduler	re-scheduler	VoIP	NRTV
PF	1-bit hyperactive	7.2%	9.1%
PF	2-bit lazy	0.6%	1.4%
MCI	1-bit hyperactive	7.3%	9.5%
MCI	2-bit lazy	0.5%	1.7%
EDF	1-bit hyperactive	7.6%	12.7%
EDF	2-bit lazy	0.8%	2.8%

Table 2. Chunk re-computation ratio

7. Conclusions and future research

In this chapter we have first presented an overview of currently investigated radio resource management solutions for OFDMA-based wireless cellular networks. We discussed advantages and weaknesses of main reference scheduling algorithms such as MCI, PF, MLWDF and EDF, in a system that implements a realistic OFDMA air interface based on the 3GPP/LTE downlink specifications where non full buffer traffic and a limited number of control channel per TTI were assumed. We focused our investigation on real-time, non real-time and coexisting real-time and non real-time traffic scenarios. We underlined that while EDF does not profit from multi-user diversity, MCI and PF schedulers target at maximizing the cell throughput regardless of the user's QoS constraints. Then we concentrated on the combining of FDPS and retransmission schedulers. We come out with two proposals.

First, we defined a novel scheduling algorithm, the HYGIENE scheduler. HYGIENE splits the resource allocation process in three steps: first, it identifies which *entities* (UE or packets) must be scheduled with high priority; second, it deals with *rushing entities*; third, remaining resources (if any) are allocated to users with highest momentary throughput. We evaluate the effectiveness of the proposed HYGIENE scheduler comparing it with the above reference schedulers. Our simulations substantiate how HYGIENE is a highly flexible and effective scheduler for a variety of traffic scenarios.

Second, we proposed a simple re-scheduling algorithm to efficiently deal with retransmissions. We propose that the *re-scheduler* checks, before reallocating chunks for NACK packet, if correct packet decoding is theoretically possible given the momentary channel instance and the pair (MCS, allocated chunk set). We base our re-scheduling strategy on the pair of information: channel outage instances and simple decoding errors (CRC). Thus, the *re-scheduler* recomputes the chunk allocation only for packets for which previous NACK transmission was in outage. The proposed method permits to reduce the residual PER while reducing the average number of retransmissions and increasing the overall cell capacity. Performance obtained is very favorable. We have better or equal performance than *1-bit hyperactive* re-scheduling while notably reducing the retransmission algorithm complexity. Furthermore, our results show how performance of non real-time QoS oriented schedulers (such as MCI and PF) can be significantly improved adopting the proposed *2-bit lazy re-scheduler*, especially with VoIP traffic flows. We have also shown by simulation that the

combination of both proposals (HYGIENE and smart re-scheduler) is an appealing solution to deal with real traffic and HARQ mechanisms.
Further work will focus on the combination of our proposals with CQI feedback schemes in order to assess the robustness of our proposals with respect to partial and inaccurate CQI reporting schemes.

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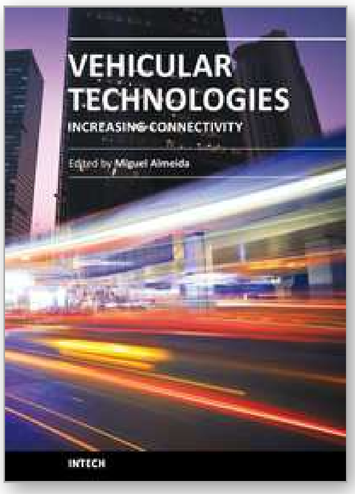

Vehicular Technologies: Increasing Connectivity
Edited by Dr Miguel Almeida

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This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.

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