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An integrated cross-layer framework of adaptive FEedback REsource allocation and Prediction for OFDMA systems

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ABSTRACT

Orthogonal frequency division multiple access (OFDMA) technology has been adopted by 4th generation (a.k.a. 4G) telecommunication systems to achieve high system spectral efficiency. A crucial research issue is how to design adaptive feedback mechanisms so that the base station can use adaptive modulation and coding (AMC) techniques to adjust its data rate based on the channel condition. This problem is even more challenging in resource-limited and heterogeneous multiuser environments such as Mobile WiMAX and long-term evolution (LTE) networks. In this paper, we develop an integrated cross-layer framework of adaptive FEedback REsource allocation and Prediction (FEREP) for OFDMA systems. The proposed framework, implemented at the base station side, is composed of three modules. The feedback window adaptation (FWA) module dynamically tunes the feedback window size for each user based on the received automatic repeat request (ARQ) messages that reflect the current channel condition. The priority-based feedback scheduling (PBFS) module then performs feedback resource allocation by taking into account the feedback window size, the user profile and the total system feedback budget. To choose adapted modulation and coding schemes (MCS), the channel quality indicator prediction (CQIP) module performs channel prediction by using recursive least square (RLS) algorithm for the users whose channel feedback has not been granted for schedule in current frame. Through extensive simulations, the proposed framework shows significant performance gain especially under stringent feedback budget constraints.

1. Introduction

Users today expect the same wireline broadband access and multimedia Internet experience from the new generation of wireless networks. Recent 3G operators' statistics have shown a significant increase in mobile data usage with a rapid growth of traffic volume [1]. Many reasons are driving this trend: the proliferation of powerful smart phone devices, the increasing audio/video streaming and IPTV demand and the diversified operators offers for price cutting flat-rate tariffs. To face this rapid growth in broadband data usage, most operators are preparing 4G solutions, among which Mobile WiMAX (IEEE 802.16 m) [2] and 3GPP LTE-Advanced are the most promising candidates.

The high bandwidth and flexibility offered by 4G systems are mainly due to the orthogonal frequency division multiple access (OFDMA) technology which has been adopted in almost all wireless broadband access standards. As shown in Fig. 1, in OFDMA systems, the base station (BS) uses adaptive modulation and coding (AMC) to change its transmission data rate based on the channel condition (characterized by channel quality indicator (CQI)), which is returned periodically by each user. Fig. 2 shows the frame structure of an OFDMA system (IEEE 802.16e [3]) in which the field channel quality feedback, consisting of a number of slots, is dedicated for the users to report their channel conditions to the BS in order to apply the AMC

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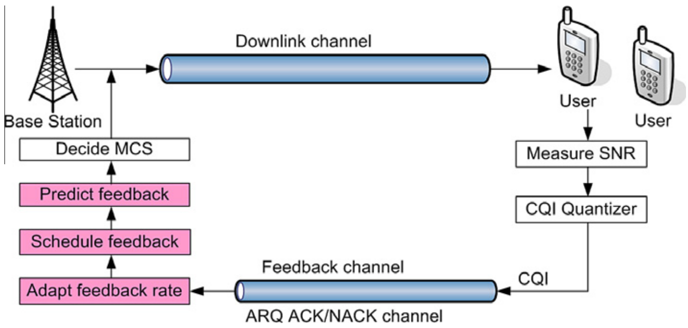

Fig. 1. OFDMA system.

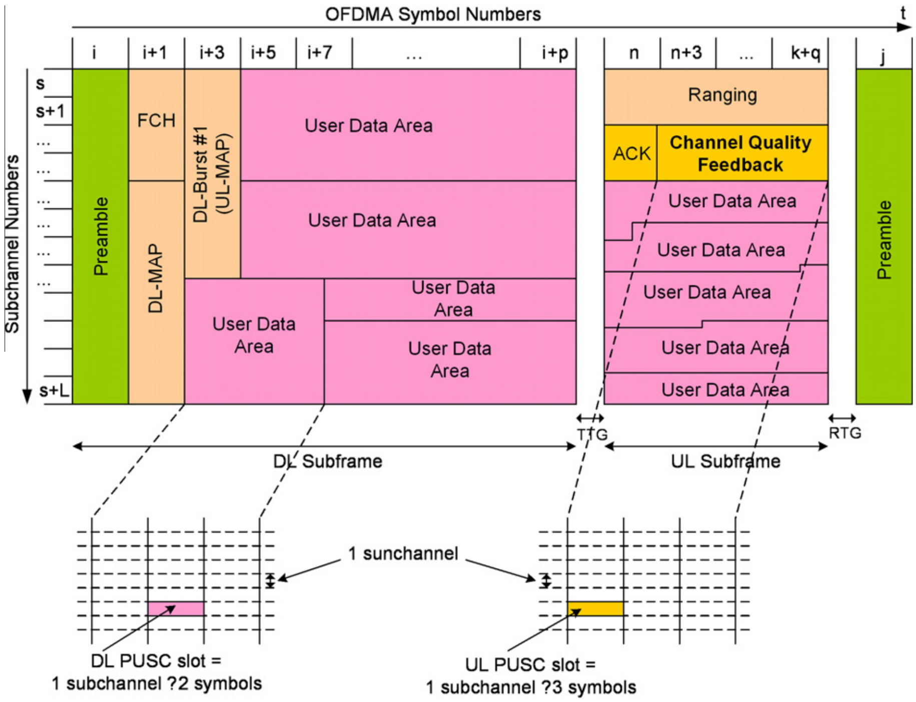

Fig. 2. Frame structure of an OFDMA system (IEEE 802.16e).

technique. As the number of slots reserved for channel feedback is limited, optimized techniques for feedback reduction are mandatory. In practical systems such as Mobile WiMAX, for example, users are allowed to send channel feedback periodically once in every w frame (w is referred to as feedback window), or aperiodically using allocation/deallocation messages.

4G networks are designed to support heterogeneous environments. On one hand, heterogeneity concerns the channel conditions experienced by users. On the other hand, the system is aimed at supporting different applications, each of which has its specific requirement in terms of quality of service (QoS) [4]. Consequently, applying the same feedback strategy for all users is definitely not adapted in these heterogeneous environments [5]. In such context, natural but crucial questions are raised: (i) how to reduce the feedback overhead for a better resource utilization without degrading the system performance, (ii) how to allocate the available feedback slots in the OFDMA frames among the active heterogeneous users to send their channel condition, given the total budget constraint, and (iii) how to design adapted feedback mechanism for heterogeneous users?

In this paper, we tackle this feedback reduction problem by proposing an integrated cross-layer framework named FEedback REsource allocation and Prediction (FEREP). The proposed framework, implemented at the BS side, is composed of three modules: the feedback window adaptation (FWA), the priority-based feedback scheduling (PBFS) and the CQI prediction (CQIP). In the FWA module, the feedback window size of each user is tuned based on the received ack/nack from automatic repeat request (ARQ) protocol that implicitly reflects the current channel condition. The PBFS module then performs feedback scheduling by taking into account the feedback window size, the user application profile, and the total system feedback budget. The CQIP module performs CQI prediction by using recursive least square (RLS) algorithm when the channel feedback is not scheduled in current frame to choose proper MCS level. Our contribution in this work is threefold. First, we propose a novel and practical framework for feedback resource allocation for OFDMA systems with total CQI feedback budget constraint. Second, our framework takes into account, for the first time, to the best of our knowledge, service differentiation in the CQI feedback allocation strategy. Finally, our framework achieves significant feedback reduction by exploiting the cross-layer strategy and the CQI prediction tool in the absence of real feedback.

The rest of this paper is structured as follows. Section 2 discusses the related works. Section 3 presents the system model. Section 4 develops the integrated cross-layer framework of adaptive feedback with prediction and provides an in-depth analysis on the proposed framework. Section 5 evaluates the proposed framework by a range of extensive simulations and finally, Section 6 concludes the paper.

2. Related works

The challenge of reducing feedback overhead started mostly with the evolution of multiuser systems to exploit the multiuser diversity [6,7]. The overhead increased exponentially in multiuser multicarrier systems like OFDMA [8–11] and with the use of advanced technologies like MIMO [12–16].

An important line of work for feedback reduction in multiuser diversity is opportunistic feedback [7,17–19,9,20,15,21–23]. Each user having CQI value above some known threshold value is allowed to send feedback. The opportunistic strategy has been proved very efficient in the case of serving a few number of users out of a large number of simultaneously active users. The opportunistic method is applied to a multichannel system in [19,9,15,23] to have feedbacks for best-n subcarriers. This scheme is designed for frequency-selective fading channels where contiguous subcarriers are assigned to each user and mainly used for low mobility cases [24]. Nevertheless, it also carries huge overhead as every user needs to send CQI for n subcarriers. The schemes [3,25–27] designed for distributed subcarriers allow to send one averaged CQI per user and generate less feedback overhead compared to previous mechanisms.

In a multicarrier multiuser system, the opportunistic feedback scheme will have no effect in feedback reduction if all the users need to be scheduled in each downlink frame. An OFDMA system (e.g. WiMAX) with 10 MHz frequency bandwidth and a simple scheduling scheme can support up to 82 voice-over-IP (VoIP) users in each downlink frame [28]. Scheduling these users with 2:1 DL and UL frame ratio consumes 40% of uplink bandwidth [29], besides other overheads from ARQ signalling and periodic ranging. To overcome this problem, modern broadband wireless systems (Mobile WiMAX, LTE) employ interval-based feedback (IBF) [3] which is based on a feedback window w. Each user sends feedback periodically in a round robin fashion once in every w frames and uses this *feedback* in next $(w-1)$ frames as *last received feedback*. Wang Xiaoyi [30] and Cohen and Grebla [31] proposed further feedback resource allocation mechanisms based on IBF. Oh and Kim [25] proposed an adaptive CQI feedback period algorithm which exploits user mobility in terms of doppler frequency. The feedback window for each user is estimated according to the doppler frequency experienced by the user. Fast users are assigned smaller feedback windows and vice versa. Iijima et al. [27] extended the work in [25]. They adapted the feedback period to different time slots according to different MCS while keeping the packet size and scheduling time fixed. Note that both schemes developed in [25,27] have to synchronize based on the maximum doppler frequency experienced in the system. Allocating the scheduling and feedback period based only on doppler spread may not be optimal since Doppler effect cannot track the users which are moving perpendicular to the BS. Besides, it is possible that the users experience a good channel condition while moving in faster speed, or vice versa.

Prediction based feedback (PBF) is proposed in [32]. Unlike IBF, PBF scheme *predicts the feedback* for next $(w-1)$ frames instead of using *last received feedback*. [32] showed that it is possible to reduce the feedback load which in terms increases the uplink capacity. However, the lack of feedback affects also the downlink capacity. Awal and Boukhatem [33] analyzed and showed that downlink degradation is almost negligible compared to the uplink gains.

The studies with imperfect CQI are done in [34,11,35,36]. The omission of CQI channel has been proposed in [37,38] by exploiting the ARQ protocol signaling for link adaptation. To reduce the feedback overhead, Duel-Hallen et al. [39,40] proposed the use of channel correlation. The authors used a long-range prediction of subcarrier correlations so that only one feedback can represent the correlated values. The prediction tool was also used in [41] to predict MIMO beamforming. The channel prediction in the frequency domain has been studied in [42]. Channel prediction in time domain has been addressed in [33,43–48].

Allocating all the uplink capacity for CQI feedback is too inefficient from a network operators point of view [49,29]. For a better resource optimization, the operators gain in limiting CQI overhead to some percentage of the total uplink capacity or the total number of users [50,51]. In this work, we propose the use of both CQI prediction and cross-layer information from ARQ protocol to adapt the feedback window for each user [52,53] under a total feedback budget constraint.

3. System model

We consider an OFDMA cellular system with bandwidth B consisting of N_c subcarriers. The system has a set $\mathcal{K}$ of K simultaneously active users communicating with a single BS as shown in Fig. 1. The subcarriers are distributed among the users using partially used subchannelization (PUSC) and each user subchannel has $N_s = N_c/K$

subcarriers. The BS and all users have one antenna each. The channel process of each user is assumed independent and stationary. The channel gain is assumed constant over a frame duration T_f, but may vary frame-by-frame. The signal received by user k at frame t, is given by

$$\vec{y}_k[t] = \mathrm{H}_k[t]\vec{x}_k[t] + \vec{n}_k[t], \quad k = 1, 2, \ldots, K, \tag{1}$$

where $\vec{x}_k[t] \in \mathbb{C}^{N_s \times 1}$ is the complex transmitted signal, $\vec{y}_k[t] \in \mathbb{C}^{N_s \times 1}$ is the complex received signal, and $\vec{n}_k[t] \in \mathbb{C}^{N_s \times 1}$ is assumed to be a zero mean complex Gaussian noise vector with variance σ_n^2; and $\mathrm{H}_k[t]$ is the diagonal channel response matrix given by $\mathrm{H}_k[t] = diag\{h_{k,1}[t], \ \ldots, h_{k,N_s}[t]\}$, where $h_{k,n}[t]$ are the complex valued wireless channel fading random processes and $h_k[t] \backsim \mathcal{CN}(0_N, \sigma_h^2)$ is i.i.d over different users. The instantaneous signal-to-noise ratio (SNR) of subcarrier i in frame t for user k is defined as $\gamma_k^i[t] = \frac{|h_{k,i}[t]|^2}{\sigma_n^2}$.

To allow the BS to apply adapted MCS, users return channel information periodically to the BS as in IEEE 802.16e [3]. The BS maintains a set $\mathcal{W}$ of feedback window w_k for each user k and allows user k to send channel feedback once in every w_k frames. The system has a total feedback budget constraint, denoted as F, meaning that each frame can carry the feedback of at most F users defined as set $\mathcal{F}$. In other words, at most F users can send feedback in a frame. If the number of users scheduled to send their feedback is larger than F, the BS should select at most F users among them to return feedback.

The information in the channel feedback sent by the users to the BS contains the CQI, a measurement of the downlink channel quality. In our study, we follow the IEEE 802.16e [3] standard by defining the CQI statistic as the average SNR[1] over all the subcarriers (except the guard and direct carrier (DC) subcarriers), defined as follows for user k:

$$\gamma_k^{avg} = \frac{1}{N_s}\sum_{i=1}^{N_s}\gamma_k^i \quad (\text{in dB}), \tag{2}$$

where γ_k^i is the estimated SNR of user k on subcarrier i. Each user sends a quantized value of this SNR as CQI feedback to the BS. It is assumed that the BS receives perfect SNR with zero-delay from the user.

We note that in case of contiguous subchannelization like band-AMC, averaged CQI does not provide the BS with any knowledge on the frequency selectivity. To cope with this channel variations in frequency selectivity, effective SNR is also adopted [54] in mobile WiMAX. Effective SNR is defined as:

$$\gamma_k^{eff} = -\beta \ln\left(\frac{1}{N_s}\sum_{i=1}^{N_s} e^{\frac{\gamma_k^i}{\beta}}\right) \quad (\text{in dB}), \tag{3}$$

where γ_k^i are the per subcarrier SNR values of user k and which are typically different in a frequency selective channel. Parameter $\beta \in \mathbb{R}$ is a coefficient dependant on the MCS level. The user reports the effective SNR to the BS, and allows the BS to decide MCS level and power boosting adjustment. In contrast to the averaged CQI in Eq. 2, the power adaptation for each effective SNR is MCS dependant and does not change linearly. For simplicity, in this study, we use the averaged CQI under PUSC assumptions $\gamma_k = \gamma_k^{avg}$. Note that since our proposed prediction mechanism using RLS (see Section 4.3) is independent of channel fading coefficients, it is also capable of producing predicted CQI using effective SNR.

Once receiving the channel feedback γ_k from a user k, the BS chooses an MCS level based on γ_k. More specifically, MCS level j, corresponding to data rate r_j, is mapped to a quantization level Q_j when $\gamma_k \in [q_j, q_{j+1})$.

As argued in the Introduction, modern broadband systems using OFDMA are aimed to support user heterogeneity. In our model, each user k is characterized by its service priority, denoted by α_k, an operator defined parameter which represents the aggregation of several users priority metrics such as QoS requirements, user profile, and the amount of payment to the operator, etc. For OFDMA based systems, service differentiation is one of the key elements. Operators are supposed to propose diversified offers for subscribers while maximizing system performance, e.g., subscribers can be virtually grouped by the operator according to different metrics (e.g. high/low tariffs, private/corporate subscriptions, sensibility/tolerance to QoS degradations) and provide for each group dedicated and differentiated treatments. In this regard, users with higher α values are supposed to get better service than those with lower α values.

4. FEREP: proposed integrated cross-layer scheme

As mentioned previously, in current standardized OFDMA systems [3,55,56], each user is assigned a feedback window without taking into account user heterogeneity in terms of application, mobility, QoS constraint, etc. However, today's wireless systems are typically serving users with different applications (e.g. VoIP and video) and mobility profiles (e.g. vehicular and pedestrian). In such context, applying a homogeneous feedback mechanism to heterogeneous users is clearly unadapted. The situation is deteriorated in case a stringent constraint on the total number of feedbacks is imposed due to the limited radio resource in OFDMA systems (i.e., only F CQI slots are dedicated for K users to send feedback while usually $K > F$). This motivates our proposition of a cross-layer framework of adaptive feedback with prediction, consisting of three modules: the feedback window adaptation (FWA), the priority-based feedback scheduling (PBFS) and the CQI prediction (CQIP).

At the beginning of each frame, FWA algorithm at the BS dynamically calculates the feedback window for each user based on the ARQ signaling with explicit ack/nack, received for the packets transmitted in previous frames. As there are only F CQI slots in each frame available to send feedback, the PBFS algorithms selects the F out of K users to send feedback in that frame based on a weighted-priority algorithm. The rest of the $(K - F)$ users which are not scheduled to send feedback in that frame, instead, their CQIs are predicted by the CQIP module based on recursive least

[1] We used the terms SNR and CQI interchangeably throughout the paper.

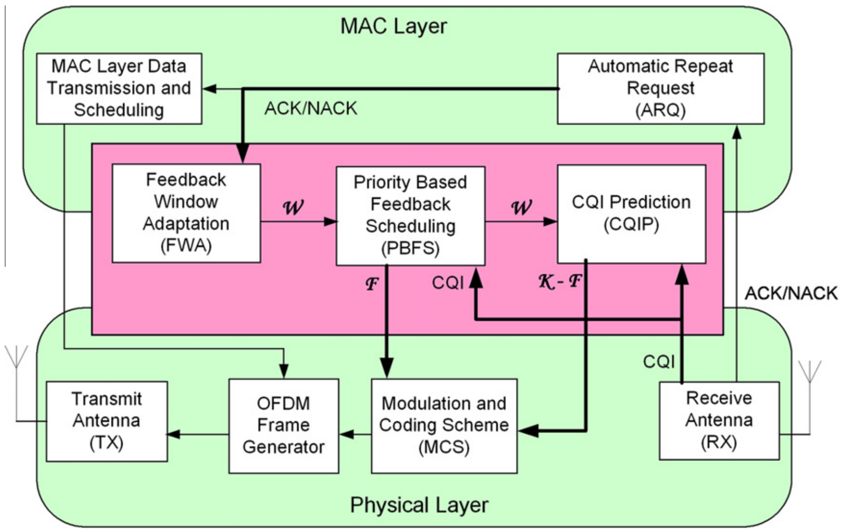

Fig. 3. FEREP Framework.

square (RLS) algorithm. Fig. 3 gives a system-level overview of the proposed framework and represents the interaction between physical and MAC layers. In the following, we provide a detailed analysis of the proposed framework modules.

4.1. Feedback window adaptation (FWA)

The objective of the FWA algorithm is to dynamically calculate the appropriate feedback window size based on users channel condition. As explained in related works, using the doppler frequency as the sole metric [27,25] for feedback adaptation may be inappropriate as a user experiencing high doppler frequency may still have sufficiently good channel to recover lost packets correctly. Another point is that in existing systems where CQI is sent once in every w frames ($w > 1$), the BS has no knowledge about the channel change within the interval between two successive CQIs. In FWA, we exploit the ack/nack packets of the ARQ protocol which are returned in every frame to adjust the feedback window size.

More specifically, if a packet is recovered by the user properly, it sends an ack frame back to the BS. Otherwise, the user sends a nack frame and the BS retransmits the packet[2]. The ARQ protocol maintains a parameter for maximum number of retransmissions $N_{re}^{\max}$. When a packet is retransmitted $N_{re}^{\max}$ times and no ack is received, it is considered lost. $N_{re}^{\max}$ is application dependant and increasing its value would violate the delay constraint for an application [57].

Algorithm 1. Feedback window adaptation procedure to calculate w_k

1: **initialization:** Set $N_{ack}^{th}(\alpha_k), w_k \leftarrow w_k^{init}, n_{ack} \leftarrow 0$,
2: **loop**
3: **if** ack received **then**
4: $n_{ack} \leftarrow n_{ack} + 1$
5: **if** $n_{ack} \geqslant N_{ack}^{th}(\alpha_k)$ **then**
6: $w_k \leftarrow w_k + 1$
7: $n_{ack} \leftarrow 0$
8: **end if**
9: **else if** nack received or timeout **then**
10: $w_k \leftarrow \max\{w_k - 1, 1\}$
11: $n_{ack} \leftarrow 0$
12: **end if**
13: **end loop**

The proposed FWA algorithm based on the above ARQ model implemented at the base station to calculate the feedback window size for user k (denoted as w_k) is shown in Algorithm 1. The core idea is to increase the feedback window size of a user when its channel condition is good, reflected by consecutively received acks, and decrease the feedback window size once a nack is received, implying a possible deterioration of the channel quality. Note that a small feedback window size means that the real measured CQI is returned to the BS more frequently (maximum, is sending in every frame) and larger window size relies on more predicted CQI at the expense of a higher risk of alteration due to the prediction error (which effect is more negligible under good channel conditions [33]).

To this end, initially (line 1), w_k is initialized to w_k^{init}. Upon receiving an ack from user k, the BS increases the counter n_{ack} which memorizes the number of consecutive received acks (lines 3–4). If the consecutive number of re-

[2] Note that our mechanism supports also implicit ARQ. In this case, retransmissions are performed after time-out.

ceived ack exceeds the threshold $N_{ack}^{th}(\alpha_k)$ which depends on the service priority α_k of user k, then the BS increases w_k by 1 and n_{ack} is reset to 0 (lines 5–8). Otherwise upon receiving a nack, the BS reduces w_k by 1(lines 9–12) and n_{ack} is reset to 0. A desirable property of the proposed FWA algorithm is that by tuning the parameters $N_{ack}^{th}(\alpha_k)$, the BS can achieve a balance between the robustness and feedback overhead, e.g., a larger value of $N_{ack}^{th}(\alpha_k)$ leads to a more conservative increase in w_k, the algorithm is thus more robust at the price of more feedback overhead caused by potential under-estimation of the feedback window size.

4.2. Priority-based feedback scheduling (PBFS) under total budget constraint

Due to limited radio resource, OFDMA based systems impose a budget constraint on the total number of feedbacks sent by the users to the BS. A critical question in this context is which users should be admitted to send feedback given the total budget constraint. In this subsection, we establish a priority-based feedback scheduling algorithm, in which the admissible users allowed to send feedback at frame t are chosen based on their priority according to their feedback window size, the last feedback sending time and their service priority α_k.

The proposed PBFS algorithm, performed after the FWA algorithm, determines which users are admitted to send CQI at frame t based on the following metric $\{M_k, k \in \mathcal{K}\}$:

$$M_k[t] = g(\alpha_k)\frac{\left(t - t_k^{\text{last}}\right)}{w_k}, \quad k \in \mathcal{K}, \tag{4}$$

where $g(\alpha_k)$ is a function of the service priority of user k, t is the current time, t_k^{last} is the time of the last received feedback from user k, and w_k is the feedback window size of user k. The priority score is thus the priority $\frac{(t-t_k^{\text{last}})}{w_k}$, determined by the feedback window and the last serving time, weighted by the user-dependent service priority. The PBFS algorithm is executed at the BS in case the number of users scheduled to send their feedback exceeds the total budget F. In this case, the PBFS algorithm admits the F users with highest priority scores. By doing so, the BS prioritizes users with bad channel condition (small feedback window size) and higher service priority while maintaining a certain fairness by integrating t_k^{last} in M_k.

To conclude this subsection, it is insightful to study the proposed PBFS algorithm from the perspective of scheduling. To this end, rewrite M_k as:

$$M_k[t] = \frac{g(\alpha_k)}{w_k}\left(t - t_k^{\text{last}}\right). \tag{5}$$

The PBFS algorithm can be essentially viewed as the round-robin scheduling scheme weighted by coefficient $\frac{g(\alpha_k)}{w_k}$ depending on the users' service priority and feedback window size. Consequently, for a user k for which the feedback should be scheduled (i.e., $w_k < t - t_k^{\text{last}}$), $\frac{\frac{g(\alpha_k)}{w_k}F}{\sum_{i\in K, w_i < t - t_i^{\text{last}}} \frac{g(\alpha_i)}{w_i}}$ slots are allocated in average among the total budget F. In the degenerated case where $\frac{g(\alpha_k)}{w_k}$ takes the same value for all users, the PBFS algorithm becomes the classical round-robin scheduling that ensures absolute fairness among users in terms of feedback resource allocation.

4.3. Channel quality indicator prediction (CQIP)

The CQIP algorithm predicts the channel condition, i.e., SNR, when the feedback is not scheduled in the current frame t. To this end, we integrate the prediction mechanism we proposed in [32]. The CQIP is a BS-side feedback prediction algorithm based on recursive least square (RLS) algorithm [58]. Upon receiving SNR $\gamma_k[t]$ from user k in frame t, the BS may predict the SNR $\hat{\gamma}_k[t+i]$, for $1 \leqslant i \leqslant w_k - 1$, so that the user does not need to send the SNR back to BS in next $w_k - 1$ frames. The predictability relies on error measures expressed in terms of a time average of the actual received SNR instead of a statistical average [58]. The error minimization objective function e_k^{RLS} for user k is defined as [58]:

$$e_k^{RLS}[t] = \sum_{j=t-w_k}^{t}\left(\lambda^{(t-j)}e_k^*[t]e_k[t]\right), \tag{6}$$

where λ is the scalar weighting factor with $0 < \lambda \leqslant 1$ that can change the performance of the prediction. The SNR is predicted for user k as [58]:

$$\hat{\gamma}_k[t] = F_k[t-1]\vec{\gamma}_{w_k}[t], \quad t \geqslant 1, \tag{7}$$

where $\hat{\gamma}_k[t]$ is the predicted SNR for time slot $t, F_k[t]$ is the w_k-th order prediction filter and $\vec{\gamma}_{w_k}[t]$ is $w_k \times 1$ vector of previous real or predicted SNRs up to time slot t. The prediction filter is updated as:

$$F_k[t] = F_k[t-1] + \vec{G}_k[t]e_k^*[t], \quad t \geqslant 1, \tag{8}$$

where $e_k^*[t]$ is the complex conjugate of $e_k[t]$, and the error $e_k[t]$ according to [58] is defined as:

$$e_k[t] = \gamma_k[t] - \hat{\gamma}_k[t], \quad t \geqslant 1, \tag{9}$$

and $\vec{G}_k[t]$ is the RLS or Kalman gain vector given by [58]:

$$\vec{G}_k[t] = \frac{\mathbf{R}_k^{-1}[t-1]\vec{\gamma}_{w_k}[t]}{\lambda + \vec{\gamma}_{w_k}^T[t]\mathbf{R}_k^{-1}[t-1]\vec{\gamma}_{w_k}[t]}, \quad t \geqslant 1. \tag{10}$$

Here, $\vec{\gamma}_{w_k}^T[t]$ is the transpose of $w_k \times 1$ vector $\vec{\gamma}_{w_k}[t]$. The matrix $\mathbf{R}_k^{-1}[t]$ is the inverse of the $w_k \times w_k$ sample covariance matrix, it can be calculated recursively as [58]:

$$\mathbf{R}_k^{-1}[t] = \frac{1}{\lambda}\left(\mathbf{R}_k^{-1}[t-1] - \vec{G}_k[t]\vec{\gamma}_{w_k}^T[t]\mathbf{R}_k^{-1}[t-1]\right), \quad t \geqslant 1. \tag{11}$$

The recursion is initialized as:

$$F_k[0] = \vec{G}_k[0] = \gamma_k[0] = 0, \quad \mathbf{R}_k^{-1}[0] = dI_{w_k w_k},$$

where $I_{w_k w_k}$ is a $w_k \times w_k$ identity matrix and d is a large positive constant.

As expressed in previous formulas, RLS prediction introduces SNR error estimations which may lead to under or over estimations compared to the real SNR. These misestimations can act on deciding lower or higher MCS levels and result in throughput and BER alteration. The effect of RLS prediction error on system performance metrics (throughput, BER and spectral efficiency) has been investigated in our previous work [33]. The analytical and simulation analysis showed that downlink degradation is almost negligible compared to the uplink gains. A cross-layer opportunistic method has been proposed in [59] to reduce the effect of under or over estimations. For more details on the prediction strategy, the reader can refer to [32,33].

5. Simulation study

In this section, we evaluate the performance of the proposed framework via extensive simulations using Matlab [60] and gain further insight on how different system parameters influence the performance. More specifically, we study the behavior of the proposed framework in a homogenous scenario where users have the same service priority α, and a heterogeneous scenario where users have different service priorities. For both scenarios, we conduct a set of simulations using two channel patterns indicative of the typical mobility profiles, the ITU pedestrian A model representing low mobility scenario of 3 km/h, and the ITU vehicular B model corresponding to high mobility scenario of 60 km/h. Then we compare the performance of FEREP with three reference mechanisms: (i) IBF the interval based feedback [3], (ii) DBF the doppler based feedback proposed in many works [25,27], (iii) OF the opportunistic feedback introduced in [7,61]. For downlink resource allocation, we

Table 1
Simulation parameters.

Parameters	Value
Channel bandwidth	10 MHz
Frame duration	5 ms
Downlink subchannelization method	PUSC (1 channel $\times$ 2 symbol)
Uplink subchannelization method	PUSC (1 channel $\times$ 3 symbol)
Number of downlink subchannels	30
Number of uplink subchannels	35
Downlink:Uplink Ratio	2:1
Number of downlink symbols	27
Number of uplink symbols	18
Slow mobility channel	ITU Ped-A 3 km/h
Fast mobility channel	ITU Veh-B 60 km/h
Cell radius	1 km
Path loss PL (d)	12 log ($4\pi d/\lambda$) – 27
Maximum number of retransmission in ARQ (N_{re}^{max})	4
VoIP packet size per frame	11.5 bytes
Video packet size per frame	121 bytes
Target BER	10^{-3}
Target PER	10^{-1}
Channel bandwidth	10 MHz
Frame duration	5 ms
Downlink subchannelization method	PUSC (1 channel $\times$ 2 symbol)
Uplink subchannelization method	PUSC (1 channel $\times$ 3 symbol)
Number of downlink subchannels	30
Number of uplink subchannels	35
Downlink:Uplink Ratio	2:1
Number of downlink symbols	27
Number of uplink symbols	18
Slow mobility channel	ITU Ped-A 3 km/h
Fast mobility channel	ITU Veh-B 60 km/h
Cell radius	1 km
Path loss PL (d)	12 log ($4\pi d/\lambda$) – 27
Maximum number of retransmission in ARQ (N_{re}^{max})	4
VoIP packet size per frame	11.5 bytes
Video packet size per frame	121 bytes

Table 2
Minimum receiver SNR required to use in MCS.

Modulation	Level	Coding	Minimum receiver SNR (db)	Bitrate
BPSK	1	1/2	3.0	1
QPSK	2	1/2	6.0	2
	3	3/4	8.5	2
16QAM	4	1/2	11.5	4
	5	3/4	15.0	4
64QAM	6	2/3	19.0	6
	7	3/4	21.0	6

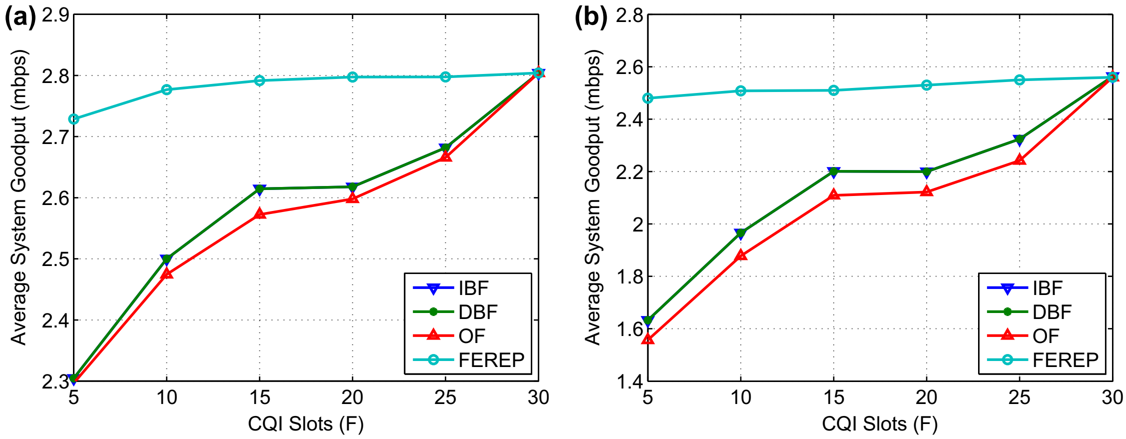

Fig. 4. System goodput for available CQI slots with homogeneous users in (a) pedestrian mobility (b) vehicular mobility.

assume that each user have enough backlogged traffic and all the users are scheduled in each frame using all three schemes.

In the IBF scheme, users are scheduled to send feedback in a round robin fashion based on their preset feedback window. Users who are not scheduled to send feedback, their last received feedbacks are used as the current channel condition according to the IEEE 802.16e standard [3] or works in [30,31]. In the DBF scheme, users feedback windows are determined based on their doppler spread frequency, and users are scheduled to send feedback in a round robin fashion using the determined feedback window. In the OF scheme, the BS broadcasts the CQI threshold γ_{th} and the users $F = \{\gamma_k | \gamma_k > \gamma_{th}, k = 1, 2, \ldots, K\}$ are allowed to send their feedback. A possible CQI feedback outage may occur if no feedback is returned (γ_{th} is overestimated). The BS then randomly selects some users to schedule in downlink using the most robust MCS level. To avoid the feedback outage problem, the BS needs to rebroadcast the CQI threshold with a smaller value. This, in response, increases the opportunity for more users to send CQI hence causing more feedback overhead. Moreover, the OF scheme works in a contention based fashion with possibility of collisions among the feedbacks. We assume the optimal case where all the feedbacks are received by the BS without any collision. Note that for $F = K$, all reference schemes as well as FEREP evolve to the optimal case in which all the users send channel feedback in each frame.

5.1. Simulation setting

We study a single-cell, single-sector system where the BS communicates with K users randomly distributed in the cell with radius 1 km. The network parameters, as shown in Table 1, are set following the IEEE 802.16e standard [3]. As mentioned previously, two channel mobility models are simulated: ITU pedestrian A (3 km/h) and ITU vehicular B (60 km/h). Each user has a session of 156 s equivalent to 31200 frames (200 frames/s for 5 ms frame duration). Among the users, 50% of them are voice over IP (VoIP) users and other 50% are video users. The VoIP users have data rate of 5.3 kbps with G723.1 Annex A format [28]. The video users have data rate of 176 kbps with H.264 format. Taking consideration of MAC header and fragmentation or packing header overhead, the data rates are 11.5 and 121 bytes, respectively per user per frame. We assume a simple downlink scheduling algorithm as in [28] where each user is scheduled in each frame. The minimum received SNR required to decide each MCS level is shown in Table 2 [3]. Each simulation is run 10 times with different seeds.

5.2. Homogenous scenario

We start with the homogenous scenario consisting of $K = 30$ users with the same service priority α. In Fig. 4, we show the effect of feedback constraint parameter F on the performance of the proposed framework, as well as the reference schemes in terms of average goodput[3]. In this scenario, F out of K users send feedback in each frame, and every user has same priority to send feedback.

The results show that FEREP outperforms the reference schemes in both mobility scenarios. The performance gain is more significant in high mobility scenario and with most stringent total feedback budget (i.e., small F), which demonstrates that in such cases, using the same feedback strategy for all users is clearly not optimal, and that the proposed adaptive feedback mechanism with prediction can effectively improve the system performance by integrating the feedback window adaptation and CQI prediction under the total feedback budget constraint. For a fixed mobility, both IBF and DBF behaves as equivalent as the doppler spread remains constant and only the fading and pathloss are affecting channel change.

The OF shows the worst performance among all the schemes in terms of system goodput. The performance of OF is expected to be better, at least compared to IBF and DBF, when a small number of users are scheduled in down-

[3] goodput = throughput - lossrate

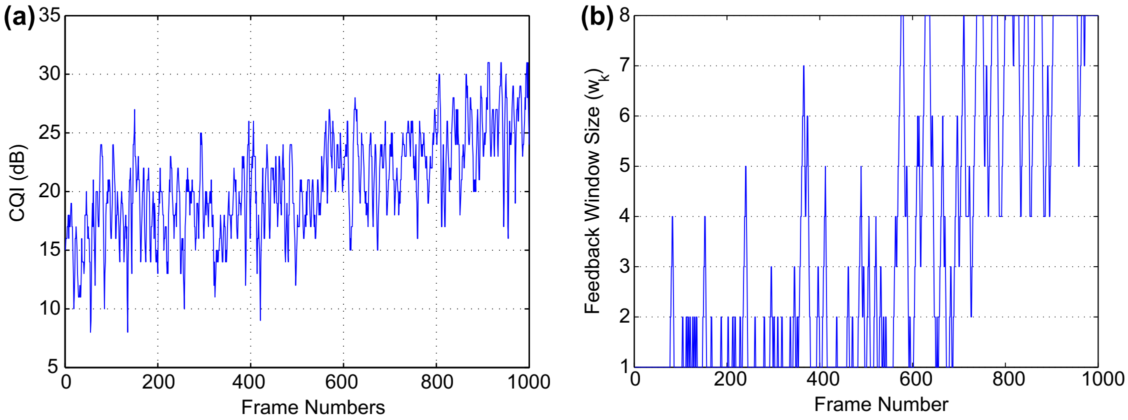

Fig. 5. (a) CQI (b) feedback window for a user with ITU vehicular B channel model.

link among many users. In this work, we are dealing with the feedback slots reduction problem when a large number of users are scheduled in downlink. In constraint feedback budget scenarios $(F < K)$, rest of the $(K - F)$ users are scheduled using the most robust MCS level (requires more physical slots) which may reduce the packet loss rate significantly at the expense of a degraded average system goodput as it exhausts the system capacity per frame.

To get a more in-depth insight on the property of the proposed framework, we study the feedback window size at the output of the feedback window adaptation (FWA) module. Fig. 5(a) plots the real channel condition from time 1 to 1000 of a vehicular user and Fig. 5b shows the correspondent feedback window size as derived by FWA. We can observe that with the average channel quality improvement over time, the average feedback window also increases. More specifically, when the channel quality varies significantly, the FWA module generates a relatively small feedback window, which allows the BS to have more channel feedback, when the channel quality variation decreases, the feedback window size increases as less feedback is required to estimate the channel condition. As a result, the FWA module dynamically tunes the feedback window size based on the channel condition, thus reaching an appropriate feedback window size.

The system parameter N_{ack}^{th} acts actively on the performance of FEREP scheme. Fig. 6 shows the results of FEREP with varying N_{ack}^{th} for VoIP and video applications for vehiculer mobility. We observe that the average feedback window is inversely proportional to N_{ack}^{th} value. As N_{ack}^{th} increases, the system acts more lately to raise the value of w. Definitely, a smaller feedback window provides more knowledge about the channel state and helps to achieve higher goodput. Besides, larger feedback window saves uplink resources with the tradeoff of downlink throughput degradation. We found from our simulation results that $N_{ack}^{th} > 4$ maintains our target BER and PER.

5.3. Heterogeneous scenario

In this subsection, we study the case of a more realistic scenario including heterogeneous users. More specifically,

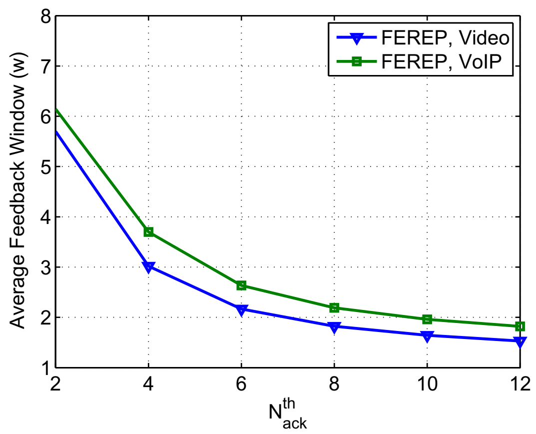

Fig. 6. Average feedback window for different N_{ack}^{th} values with homogeneous users in vehicular mobility.

7 VoIP users and 7 video users are high priority users with service priority $\alpha_k = 1.0$, while the others are low priority users with $\alpha_k = 0.5$. $g(\alpha_k)$ is set to a linear function $g(\alpha_k) = \alpha_k$. Fig. 7 shows the system goodput as a function of F. We observe the same behavior as in the homogenous scenario, i.e., our proposed framework outperforms the reference schemes in both cases with more significant gain for high mobility channel and more stringent feedback budget.

We then study the average goodput of individual users of different classes for VoIP and video applications in Figs. 8 and 9, respectively. We report the observation that the high priority users always enjoy better performance in terms of goodput. Such performance gap between high priority and low priority users is more significant for video application. This can be explained as follows: as the packet size for VoIP is much smaller than that of video, the difference in the feedback window has much less impact on the final goodput for VoIP users than for video users. Indeed, we do observe significant difference in feedback window

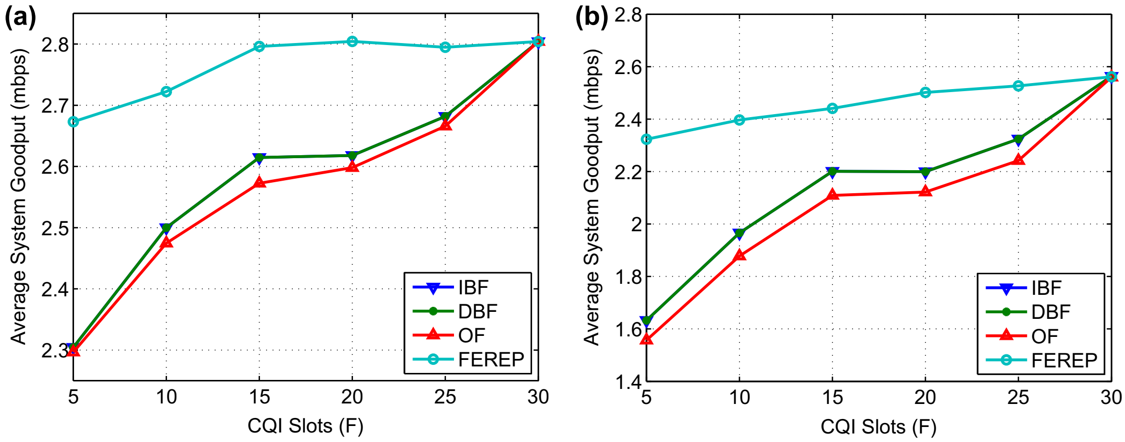

Fig. 7. System goodput for available CQI slots with heterogeneous users in (a) pedestrian mobility (b) vehicular mobility ($I = 1$).

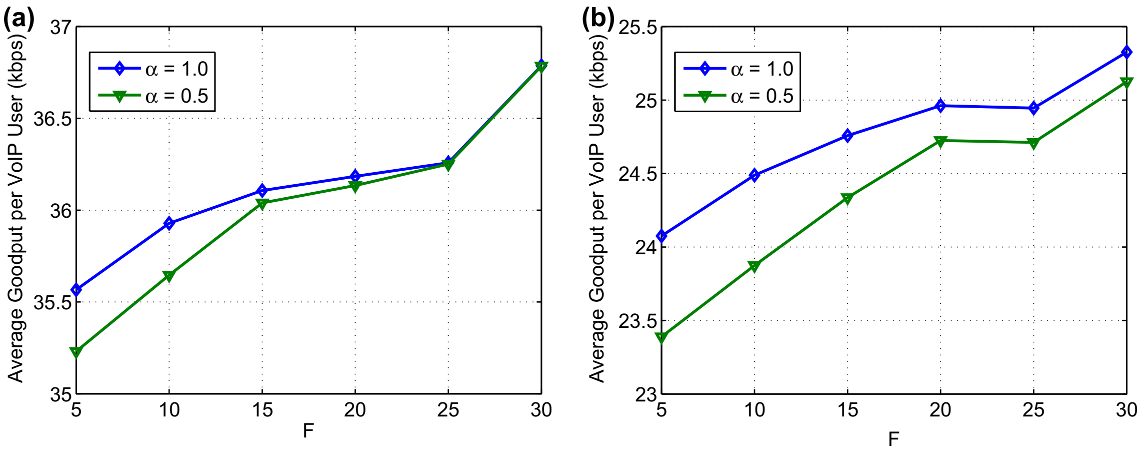

Fig. 8. System goodput for available CQI slots with heterogeneous VoIP users in (a) pedestrian mobility (b) vehicular mobility ($I = 1$).

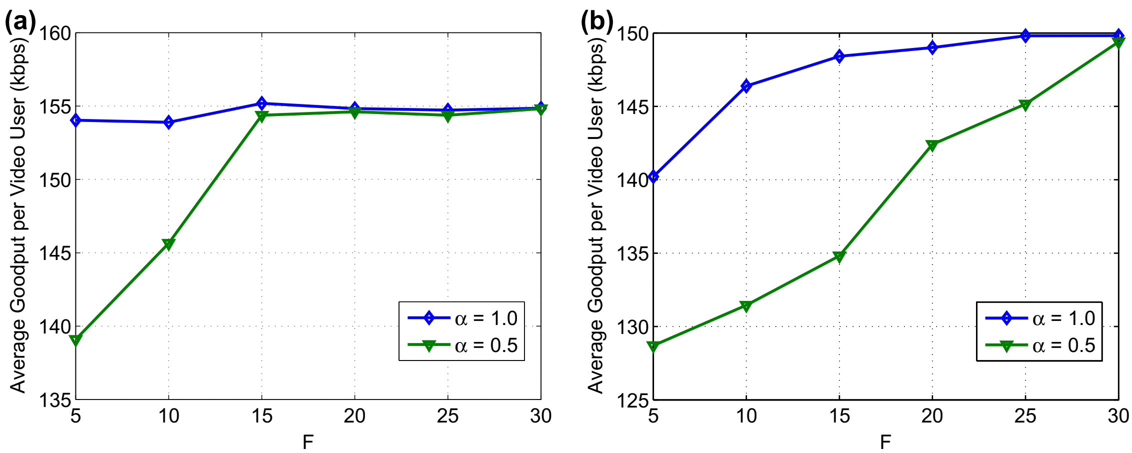

Fig. 9. System goodput for available CQI slots with heterogeneous video users in (a) pedestrian mobility (b) vehicular mobility.

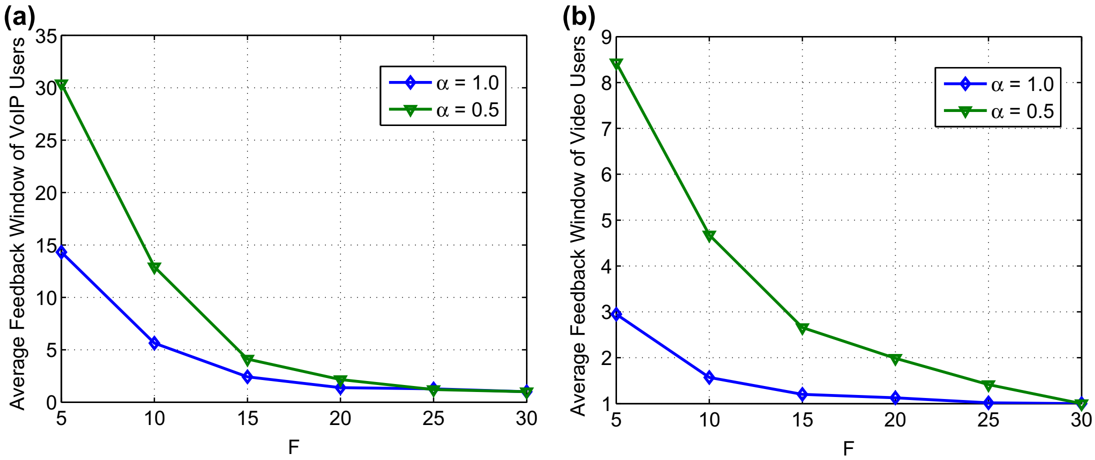

Fig. 10. Average feedback window for available CQI slots in vehicular mobility with (a) VoIP users (b) video users.

(thanks to the FWA module, high priority users have smaller feedback window size, thus can send feedback more frequently), as shown in Fig. 10. The above results demonstrate that the proposed framework is adapted to heterogeneous network scenarios and can be used easily to realize efficient service differentiation.

6. Conclusion and future works

In this paper, we have developed an integrated cross-layer framework of adaptive feedback with prediction for OFDMA systems. The proposed framework, implemented at the BS side, is composed of three modules. The feedback window adaptation (FWA) module dynamically tunes the feedback window size for the users based on the received ack/nack messages that reflect their current channel conditions. The priority-based feedback scheduling (PBFS) module then performs feedback scheduling by taking into account the feedback window size, the user profile and the total system feedback budget. The channel quality indicator prediction (CQIP) module performs CQI prediction by using recursive least square (RLS) algorithm for the users whose channel feedback has not been granted for scheduling in current frame. Through extensive simulations, the proposed framework shows significant performance gain especially in the case with a stringent feedback budget constraint. Mobile WiMAX and LTE operators can easily take advantage of this framework to efficiently reduce feedback overhead while maintaining a high system performance in terms of radio resource utilization, service differentiation and adaptability.

Besides all the results presented above, there are many interesting perspectives left to deal with in the future. It would be interesting to see the combination of ARQ and doppler frequency for a more tightly controlled channel and application aware feedback window adaptation. With the integration of MIMO features, the feedback overhead is drastically increasing with the number of transmit and receive antennas. An essential investigation can be the adaptation of FEREP in open loop and closed loop MIMO scenarios. In the open loop MIMO, it is required for each user to send only one CQI value (the best one) instead of the whole CQI matrix. Our ongoing investigation shows that the application of FEREP in open loop MIMO is more intuitive than close loop MIMO.

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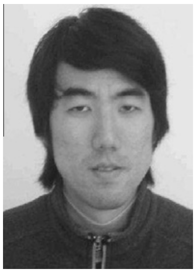

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