Superposition-Coding Aided Multiplexed Hybrid ARQ Scheme for Improved Link-layer Transmission Efficiency

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Abstract— **In this paper, we propose a novel superposition coding aided multiplexed Hybrid Automatic Repeat reQuest (HARQ) scheme for the sake of improving the link-layer transmission efficiency. The detailed system design is presented and the achievable link-layer packet error rate as well as the link-layer transmission efficiency metric is quantified. It is demonstrated that our scheme substantially improves the attainable transmission efficiency and it is particularly suitable for delay-sensitive services.**

I. INTRODUCTION

For the sake of further improving the robustness against link adaptation inaccuracy due to various implementation impairments, such as channel estimation/prediction errors, feedback delay, unpredictable co-channel interference etc, Hybrid Automatic Repeat reQuest (HARQ) schemes have been proposed [1], [2], which combine channel coding with the ARQ protocol. It has been considered as one of the key link-layer techniques in various standards, such as High Speed Packet Access (HSPA) [2], the Third-Generation Partnership Project's (3GPP) Long Term Evolution (LTE) initiative [3] and in the Worldwide Interoperability for Microwave Access (WIMAX) system [4]. Most of the research disseminated in the open literature was dedicated to the aspects of information-theoretic analysis [5], [6], to creating specifically designed channel codes [7], [8] and to the modelling of HARQ schemes used for system-level simulations [9], [10].

From a cross-layer point of view [11], HARQ also plays a crucial role in the overall system's transmission efficiency. In order to avoid the unnecessary congestion control of the Transmission Control Protocol (TCP) layer due to physical channel errors, HARQ schemes attempt to conceal the channel-induced packet loss events from the TCP-enabled transmitter by reducing the effects of wireless link errors with the aid of channel coding combined with retransmissions on a prompt packet-based timescale. This solution is appealing as it does not incur the typical overhead associated with TCP-awareness and yet obeys the TCP semantics. However, this HARQ aided approach introduces extra delay due to local link layer retransmissions, which may potentially lead to a timeout and hence may trigger the slow-start phase of the TCP transmission. Hence, these two interacting retransmission functions jointly contribute towards the overall efficiency of the system. Against this backdrop, in this paper we aim at improving the overall *end-to-end* transmission efficiency by reducing the link layer's *hop-by-hop* HARQ retransmission delay with the aid of our proposed superposition coding aided Multiplexed HARQ (M-HARQ) scheme, which jointly encodes the current new packet to be transmitted and any packets that are about to be retransmitted. In other words, the link-layer retransmissions are embedded in the next new packet's transmission, which avoids any potential throughput reduction imposed by retransmissions although naturally, they do impose additional interference. A similar idea was proposed in [12], which requires a specifically designed channel code and its application is limited to twin-packet joint transmissions. As a benefit, our proposed scheme is capable of jointly and simultaneously transmitting multiple packets and it is equally applicable to both Type I and II HARQ techniques. Hence, the advocated technique can be seamlessly integrated with diverse existing and future systems.

In a nutshell, the contribution of this paper is that *we propose a novel Multiplexed HARQ (M-HARQ) scheme, which improves the link-layer transmission efficiency at the cost of a marginal link-layer Packet Error Ratio (PER) performance degradation, which is imposed by the associated slight interference degradation.*

The rest of the paper is organized as follows. In Section II, we provide a general description of the classic HARQ approach. Furthermore, the structure of our proposed M-HARQ arrangement is described, followed by the associated encoding and iterative decoding algorithms. In Section III, both the link layer PER performance and the transmission efficiency of both the conventional HARQ and the proposed M-HARQ scheme are evaluated and discussed. Finally, we conclude our discourse in Section IV.

II. MULTIPLEXED HYBRID ARQ

A. Conventional Approach

Being a physical-layer-aware ARQ scheme, HARQ combines the Cyclic Redundancy Check (CRC) encoding function

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of the link layer with channel coding in the physical layer. In HARQ, the receiver asks for a packet's retransmission using the reverse-direction channel with the aid of a single-bit Negative-ACKnowledgement (NACK) flag, whenever its currently decoded packet is deemed to be erroneous based on the decision of the CRC scheme. In general, the retransmissions in ARQ-aided systems can be carried out in different manners, for example using a Type-I Packet Combing (PC) scheme and a Type-II Incremental Redundancy (IR) scheme. In this paper, we elaborate on Type-I HARQ, although our proposed scheme is equally applicable to both types. In Type-I HARQ, the same coded packet is used in consecutive retransmissions, allowing the receiver having a sufficiently large memory to perform soft combining of the various replicas of the packets before decoding. Naturally, each packet is also individually decodable for a receiver without sufficient memory to decode each replica of retransmitted packets, although typically this results in a residual PER penalty or in an increased number of retransmissions.

Following the above conceptual introduction, let us now describe it mathematically. The information arriving from the upper layer, which is referred to here as a *frame*, is partitioned into M *packets* of equal length N_i, $\mathbf{u}_m \in \{0,1\}^{N_i}, m \in [1, M]$. These packets are protected by the channel coding function $f_{c,v} \in \Omega = \{f_1, \dots, f_V\}$ of rate $r_{c,v} \in \mathrm{R} = \{r_1, \dots, r_V\}$, where Ω and R represent a set of predefined discrete rate-compatible codes and their corresponding rates. The selection of a particular code-rate is based on the CQI controlling the link adaptation procedure. The maximum number of retransmissions is $L < M$ and we assume that an unsuccessful packet delivery occurs, when the system activated the maximum number of L retransmissions, i.e. had a total of $(L+1)$ transmission attempts. For Type-I HARQ, the same coded packet is repeated L times, i.e. we have $f^0_{c,v}(\mathbf{u}_m) = f^l_v(\mathbf{u}_m), l \in [1, L]$, where the superscript $'0'$ stands for the initial transmission. After successfully decoding the mth packet during the $(L+1)$st transmission attempt, the transmission of the $(m+1)$st packet is activated. The whole process is illustrated in Fig. 1.

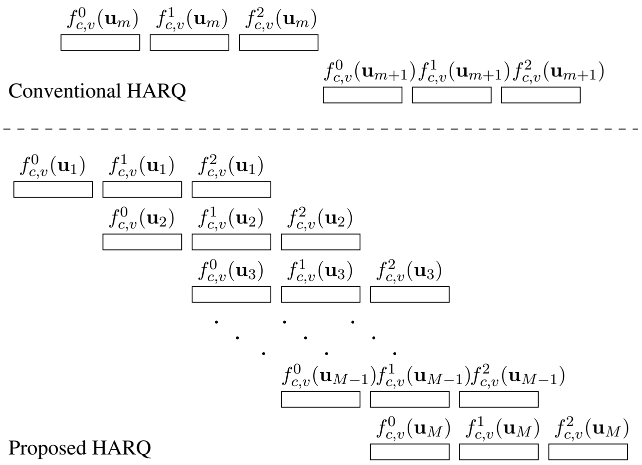

Fig. 1. Classic HARQ and the proposed multiplexed HARQ in conjunction with $L = 2$.

B. Proposed Approach

The strategy of transmitting the next new packet only when the successful reception of the current one was confirmed is highly inefficient, which is analogous to the widely recognized drawback of conventional Stop-and-Wait ARQ [1]. However, if the receiver is capable of tolerating a modest amount of additional interference, the next new packet can be simultaneously transmitted with the retransmissions of the previous $K \in [1, L]$ erroneous packets, as seen in Fig 1. In other words, M new packets are continuously transmitted, while the K erroneous packets are transmitted on a virtual channel, appropriately combined with the new packets.

1) Structure: In general, different packets require different number of retransmissions, depending on the instantaneous channel conditions. We consider the worst-case scenario, where each packet exploited the maximum number of retransmissions L, so that we can evaluate the maximum of the PER after L retransmissions. In the worst-case scenario considered and when employing the superposition coding scheme to be introduced shortly, the resultant interference of our M-HARQ arrangement becomes similar to that of the Inter-Symbol-Interference (ISI) effects experienced for transmission over a dispersive channel in the absence of HARQ transmissions. Analogously, our scheme may be interpreted as generating Inter-Packet-Interference (IPI) and hence can be represented with the aid of a Toeplitz-matrix in the form of:

$$\mathbf{G}_{M-HARQ} = \begin{bmatrix} 1 & 1 & 1 & & & & \\ & 1 & 1 & 1 & & & \\ & & 1 & 1 & 1 & & \\ & & & 1 & 1 & 1 & \\ & & & & 1 & 1 & 1 \end{bmatrix}. \tag{1}$$

This band-structured matrix describes the proposed M-HARQ scheme for the specific example of $L = 2$ and $M = 5$, where a total of $M + L = 7$ packet transmissions are required. More generally, it may be inferred from Fig 1 that the conventional scheme requires a total of $M_r = M(L+1)$ packet transmissions, while our scheme necessitates only $M_r = M + L$ transmissions.

Remarks: The structure of our M-HARQ scheme may also be related to the relaying scenario, where the continuously transmitted M packets are oriented from the direct source-to-destination link while the maximum of L retransmissions of a specific packet are activated during the consecutive original packet transmissions from a set of L relay-to-destination links. Hence, the rate-loss of the consecutive retransmissions of a packet due to orthogonal time diversity achieved by the conventional HARQ scheme is mitigated by the proposed non-orthogonal spatial diversity approach facilitated by the relaying scenario considered. Relaying scenario was also referred to as a so-called 'opportunistic multipath scenario' [13], which more explicitly justifies the efficiency of our proposed M-HARQ scheme.

2) Encoding: Generally speaking, the joint encoding function F of the mth transmission can be represented as

$F(\mathbf{u}_{a_1}, \ldots, \mathbf{u}_{a_2})$, where we have:

$$\begin{cases} (a_1, a_2) = (m, 1) & 1 \leq m < L, \\ (a_1, a_2) = (m, m-L) & L \leq m \leq M, \\ (a_1, a_2) = (M, m-L) & M < m \leq M+L. \end{cases} \tag{2}$$

Although in principle specifically designed coding functions may be created, we opt for the powerful superposition coding concept in this paper:

$$F(\cdot) \;=\; \sum_{i=a_2}^{a_1} \rho_i e^{j\theta_i} f_m \left[f_{c,v}^{m-i}(\mathbf{u}_i) \right], \tag{3}$$

where each superimposed packet is referred to as a layer, while ρ_i and $\theta_i \in [0, \pi)$ denote the layer-specific amplitude- and phase-rotation, respectively. The benefit of choosing this particular superposition coding technique is that by opting for this simple linear operation, the specific modulation function $f_m(\cdot)$ and channel coding function $f_{c,v}(\cdot)$ of the individual layers may be retained. Imposing the associated phase rotation θ_i has two benefits, namely that of reducing the Peak-to-Average Power Ratio (PAPR) of the transmitted signal and making the multiple layers more distinguishable. In this paper, an identical amplitude allocation and uniform phase rotations are employed for the individual superimposed layers.

3) Decoding: Our M-HARQ scheme employs iterative Multiple Packets Detection (MPD) and Channel Decoding (DEC) exchanging extrinsic information between these two receiver components, as seen in Fig. 2. We focus our attention on the MPD algorithm, since the choice of the DEC algorithm depends on the specific channel code employed. A host of MPD schemes may be invoked, including the powerful but high-complexity Maximum Likelihood (ML) detection scheme, sphere decoding [14] etc. Here we opt for employing a low-complexity soft interference cancellation scheme.

The signal received after the mth packet's transmission may be represented as:

$$\mathbf{y} = \sum_{i=a_2}^{a_1} h_m^b \rho_i e^{j\theta_i} f_m \left[f_{c,v}^{m-i}(\mathbf{u}_i) \right] + \mathbf{n}, \tag{4}$$

where h_m^b is the block-fading channel's impulse response and $h_i = h_m \rho_i e^{j\theta_i}$ denotes the ith layer's equivalent channel gain, while $n \sim \mathcal{CN}(0, N_0)$ is the additive circulant complex Gaussian noise process having a variance of $\sigma^2 = N_0/2$ per dimension. When denoting the modulated packet as $\mathbf{x}_i = f_m \left[f_{c,v}^{m-i}(\mathbf{u}_i) \right]$, we consider the nth symbol of the mth transmission packet and aim for the detection of the jth layer's symbol $x_j = \mathbf{x}_j(n)$, then Eq. 4 may be written as

$$y = h_j x_j + \xi, \tag{5}$$

where ξ denotes the residual interference plus noise. By approximating ξ as a joint Gaussian random vector, which can be justified by the central limit theorem, we can model the extrinsic symbol probability as:

$$\mathrm{Pr}^e(x_j = x) \quad \propto \quad \exp\left[-|y - \hat{\xi} - h_j x|^2 / 2V_\xi \right], \tag{6}$$

where $x \in A$ is the particular realization drawn from the modulation alphabet A. The estimated value of ξ and its variance may be expressed as

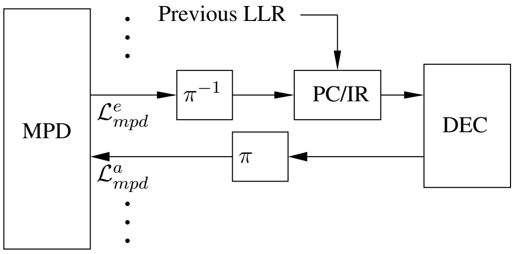

Fig. 2. Iterative receiver architecture of the mth packet's reception.

$$\hat{\xi} \;=\; \sum_{i=a_2}^{a_1} h_i \hat{x}_i - h_j \hat{x}_j, \tag{7}$$

$$V_\xi \;=\; \sum_{i=a_2}^{a_1} v_i |h_i|^2 + \sigma^2 - v_j |h_j|^2, \tag{8}$$

where the soft symbol $\hat{x}_i$ and the 'instantaneous' variance v_i are given by:

$$\hat{x}_i \;=\; \sum_{x \in A} x \mathrm{Pr}^a(x_j = x), \tag{9}$$

$$v_i \;=\; \sum_{x \in A} |x|^2 \mathrm{Pr}^a(x_j = x) - |\hat{x}_i|^2. \tag{10}$$

For the decoder of a binary code, the extrinsic non-binary symbol probability $\mathrm{Pr}^e(x_j)$ may be converted to the bit-based extrinsic Logarithmic Likelihood Ratio (LLR) $\mathcal{L}_{mpd}^e(d_j^q), q \in [1, Q]$, where we have $Q = \log_2 |A|$ and $|A|$ is the cardinality, i.e. the number of phases in the modulation alphabet A. The extrinsic LLR of the qth bit is thus given by:

$$\mathcal{L}_{mpd}^e(d_j^q) = \log_2 \frac{\sum_{x \in A_q^+} \mathrm{Pr}^e(x_j = x) \mathrm{Pr}^a(x_j = x)}{\sum_{x \in A_q^-} \mathrm{Pr}^e(x_j = x) \mathrm{Pr}^a(x_j = x)}, \tag{11}$$

where A_q^+ and A_q^- denotes the two subsets of A hosting symbols with their qth bit being +1 and -1, respectively. It can be seen from Eq. (11) that in the derivation of the extrinsic information $\mathcal{L}_{mpd}^e(d_j^q)$, only the *a priori* symbol probability $\mathrm{Pr}^a(x_j = x)$ is needed, which is given by:

$$\mathrm{Pr}^a(x_j = x) = \prod_{q \in [1,Q]} \frac{1}{2} \left\{ 1 + x^q \tanh\left[\mathcal{L}_{mpd}^a(d_j^q)/2 \right] \right\}, \tag{12}$$

where $x^q \in \{\pm 1\}$ is the qth bit's polarity in symbol x. This corresponds to a bit-LLR to symbol-probability conversion, where the bit LLR $\mathcal{L}_{mpd}^a(d_j^q)$ is gleaned from the output of the DEC block of Fig 2.

The jth layer's extrinsic LLR $\mathcal{L}_{mpd}^e(d_j^q)$ for the mth packet's transmission is then maximum-ratio-combined with the corresponding previously detected LLRs stored in the receiver's buffer, when Type-I HARQ is employed before soft decoding. When Type-II HARQ is used, the appropriately concatenated detected LLRs of all the past $K \in [1, L]$ retransmission attempts jointly constitute a codeword, which is then subjected to rate-compatible soft decoding.

Remarks: Instead of superposition coding, multiple packets may be orthogonally multiplexed within a specific transmission attempt without imposing any IPI. However, maintaining orthogonality amongst the packets requires additional Direct Sequence (DS)-spreading of the original channel coded packet, hence resulting in a rate-loss. Since orthogonal channel codes are hard to design, we may exploit the multiplexing capability inherently provided by channel codes having a rate less than unity [15] by differentiating the layers with the aid of their unique, layer-specific channel codes. Naturally, this is achieved at the cost of an increased complexity and marginal PER performance degradation.

III. PERFORMANCE EVALUATION

A. *PER Investigations*

Let us now evaluate the link layer PER performance of our proposed M-HARQ scheme. Fig. 3 shows the PER performance of the proposed arrangement against that of the conventional scheme for a total of $L + 1 = 3$ transmissions employing Type-I HARQ. In practice, a total of two or three transmissions are sufficient, since the HARQ scheme acts like a 'safety net' in support of the link adaptation procedure, which is capable of preventing most of the potential packet loss events. In our simulations, each packet of length $N_i = 256$ bits is QPSK modulated and channel coded by a rate-1/3 irregular systematic Repeat Accumulate (RA) code [16]. A Rayleigh distributed block-fading channel is used and the feedback channel conveying the NACK indicator is assumed to be error-free. Again, we consider the worst case scenario, where each of the M packets employs the maximum affordable number of $L = 2$ retransmissions.

In general, according to the Toeplitz-matrix-like arrangement having L number of retransmissions, we may investigate the PER of all the $(L + 1)$ transmissions for each of the first $(L + 1)$ packets, since they correspond to different typical interference patterns. For instance, when $L = 2$ is considered, the number of layers for each of the $L + 1 = 3$ transmissions of the $L + 1 = 3$ first packets is given by $\Omega_1 = [1, 2, 3]$, $\Omega_2 = [2, 3, 3]$ and $\Omega_3 = [3, 3, 3]$. Fig. 3 suggests that during the first transmission the PER performance of our proposed scheme is the same as that of the conventional scheme. By contrast, for two and three transmissions, there is an observable but marginal PER degradation for our proposed scheme compared to that of the conventional one. Apart from this slight difference, all packets experience a near-identical PER performance.

B. *Efficiency evaluation*

Let us first define the normalised effective throughput η as the product of the throughput per packet η_0 and the total number of packets M divided by the total number M_r of transmissions required, yielding $\eta = \eta_0 M/M_r$, where the per-packet throughput is given by:

$$\eta_0(\gamma_b) = r \cdot b \left[1 - p_e(\gamma_b)\right], \tag{13}$$

where r and b are the channel coding rate and the number of bits per symbol determined by the modulation scheme employed. Furthermore, p_e denotes the link layer's PER as a function of the Signal-to-Noise-Ratio per-bit denoted by γ_b. This metric assumes that each packet exhausts all the L retransmissions for the sake of simplified comparisons.

Let us now investigate the link layer's effective throughput η for both our proposed M-HARQ scheme and for the conventional scheme. The PER p_e versus the SNR γ_b per bit of both schemes was approximated by a 6th-order polynomial fitted to the simulated curves shown in Fig. 3. Then, the normalised effective throughput was calculated and plotted in Fig. 4. Observe in Fig. 4 the significantly improved effective throughput of our proposed M-HARQ arrangement as compared to that of the conventional one for both $M = 4$ and $M = 12$. When the total number of transmitted packets M is significantly higher than L, the effective throughput η of our proposed scheme approaches that of the single-transmission scenario, which can be verified by comparing the results of both the $L = 1$ and $L = 2$ scenarios corresponding to $M = 4$ and $M = 12$ in Fig. 4, where the $L = 0$ curve is printed using the continuous line. This implies that there is only a marginal retransmission delay penalty for our proposed M-HARQ scheme for $M \to \infty$.

More explicitly, the delay penalty may be related to the reduction of the effective throughput by a factor of M/M_r, which is $1/(L+1)$ for the conventional scheme and $M/(M + L) \approx 1$ for our proposed scheme for $M \to \infty$. For example, as illustrated in Fig. 4, where point A related to our M-HARQ scheme is calculated as $\eta_A(p_e \approx 0) = r \cdot b[1 - p_e(\gamma_b)]M/(M + L) = 0.44$ and point B related to the conventional scheme is calculated as $\eta_B(p_e \approx 0) = r \cdot b[1 - p_e(\gamma_b)]/(L + 1) = 0.22$, where we have $M = 4$, $L = 2$ and $r = 1/3$ is the channel code rate, while $b = 2$ for the QPSK scheme employed and $p_e(\gamma_b = 20) \approx 0$ for both scenarios. Thus, for $M = 4$ and a total of $L = 2$ retransmissions, we have a throughput penalty of 1/3 for the conventional scheme, while a throughput penalty of 2/3 is observed for our proposed M-HARQ scheme.

C. *Discussion*

Let us now discuss both the limitations and the beneficial applications of the M-HARQ arrangement. Our proposed scheme is based on the superposition coding approach and hence the resultant composite packet of multiple superimposed layers becomes effectively 'interference-limited'. Therefore, the per-layer throughput rate should not be excessive in order to ensure that the decoded PER remains low and approaches the single-layer best-case performance, as illustrated in Fig. 3. More explicitly, this requirement discourages the employment of high-throughput, but interference-sensitive high-PER, high-order modulation schemes, although sophisticated MPD algorithms may be employed to relax this requirement, provided that the complexity imposed remains affordable.

Furthermore, relatively low-rate channel codes are preferred for the sake of supporting the low PER transmission of multiple superimposed layers at a near-single-layer PER performance. Since the number of retransmissions L is typically low in practice, so is the number of superimposed layers. Hence for example different channel codes and/or interleavers may be used to separate the layers using the principles of channel code aided [17] or interleave division multiplexing [18]. Alternatively, orthogonal spreading sequences can be employed

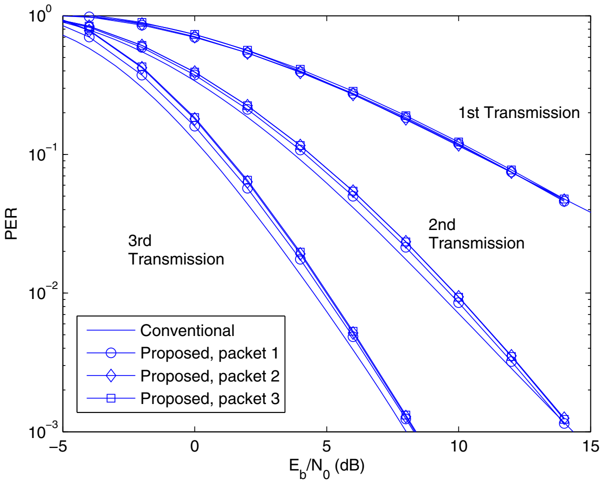

Fig. 3. The PER performance of all $L+1=3$ transmissions for both the conventional HARQ and the proposed M-HARQ scheme and for the first $L+1=3$ packets of the proposed M-HARQ scheme.

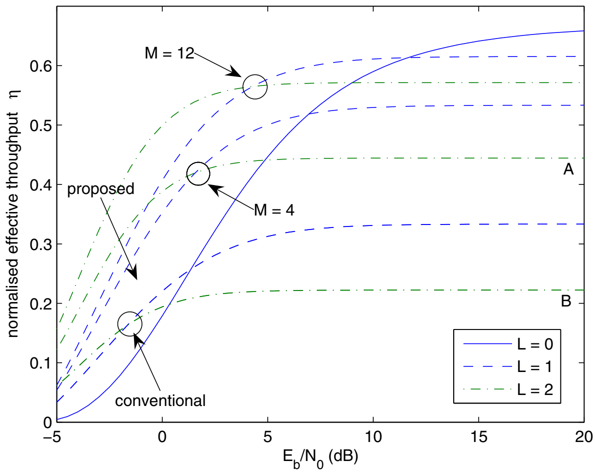

Fig. 4. The effective throughput of the first and second retransmissions for both the conventional HARQ and the proposed M-HARQ scheme. Point A related to our M-HARQ scheme is calculated as $\eta_A(p_e \approx 0) = r \cdot b[1 - p_e(\gamma_b)]M/(M+L) = 0.44$ and point B related to the conventional scheme is calculated as $\eta_B(p_e \approx 0) = r \cdot b[1 - p_e(\gamma_b)]/(L+1) = 0.22$, where we have $M=4$, $L=2$ and $r=1/3$ is the channel code rate, while $b=2$ for the QPSK scheme employed and $p_e(\gamma_b = 20) \approx 0$ for both scenarios.

for separating the layers at the cost of reducing their effective throughput proportionately to the spreading factor. Furthermore, in our investigations, only a Type-I HARQ scheme was employed based on the argument that Type-II HARQ provides a limited extra gain over Type-I HARQ for low-order modulation and low-rate channel coding [19], although the employment of Type-II HARQ is also straightforward.

IV. CONCLUSION

In this paper, a novel superposition-aided multiplexed HARQ scheme was proposed, which is capable of substantially improving the link layer's effective throughput for all transmitted packets at a marginal PER performance degradation. This improved link layer transmission efficiency also contributed towards an improved overall end-to-end transmission efficiency. Our superposition coding aided arrangement may be readily integrated with existing systems without substantially modifying the current design. It is particularly suitable for delay-sensitive low-rate services and for providing cell-edge users with an improved end-to-end throughput and/or transmission integrity.

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