NOVEL CROSS-LAYER SCHEME FOR VIDEO TRANSMISSION OVER LTE-BASED WIRELESS SYSTEMS

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ABSTRACT

In this paper, a novel cross-layer scheme is presented for video transmission over LTE-based wireless systems. The proposed cross-layer scheme takes into account parameters from the application layer (I-based versus P-based packets), MAC Layer (Scheduling packets according to their importance) and Physical Layer (Linear Precoding). All these parameters are considered within a novel resource allocation algorithm with transmission rate constraints suitable for video applications. Simulations results have shown that the proposed cross-layer scheme performs better in terms of system throughput and perceived video quality against similar cross-layer schemes.

Index Terms— AVC/H.264, LTE, MIMO, OFDMA, SDMA, Cross-Layer Resource Allocation

1. INTRODUCTION

Long Terminal Evolution (LTE) is the evolution of the UMTS technology towards the 4G communications. LTE is designed to offer high spectral efficiency, low latency and high peak data rates while providing at the same time interoperability and service continuity with the existing UMTS networks [1]. In the two lower layers of LTE architecture, the most advanced techniques have been integrated. In the PHY layer, the benefits of MIMO, OFDMA and Space-Division Multiple Access (SDMA) are exploited while in MAC layer, dynamic priority handling and HARQ are considered as compact components of the system [2]. As a result, LTE's flexible air interface with integrated Quality of Service (QoS) will support services with strict characteristics such as VoIP and video streaming.

The classical wireless system design approach, which is based on Open System Interconnection (OSI), may not lead to highly efficient solutions in terms of service provisioning for applications with strict QoS characteristics. Possibly, such an approach does not exploit efficiently all the available resources. This is evident in multiuser communication scenario where many users with different requirements compete for the same resources [3]. In the opposite, significant performance benefits may be obtained when a cross-layer design is followed [4]. Under this scope, overall system performance may be highly enhanced by cooperation between the upper and the lower layers of the system [5]. In general, the challenge of every cross-layer scheme is to organize entities that belong in different layers in a way that it is convenient not only for each individual layer but for all the cooperated layers.

In recent years, many PHY/MAC cross-layer schemes have been proposed in the literature. In [6], the problem of cross-layer design over PHY and MAC layers has been examined for the multiuser OFDMA broadcast system. Different Resource Allocation (RA) algorithms have been proposed that aim to optimize generic utility functions. In [7], [8] and [9] packet scheduling is combined with efficient RA algorithms to maximize system throughput under constraints that guarantees transmission rate and packet delay. More packet level QoS performance metrics, such as packet drop probability, jitter and perceived QoS are discussed in [10], [11], [12]. In [13], [14] cross-layer is applied on MIMO OFDMA-based systems. In [15], the additional offered degrees of freedom by the usage of multiple antennas enabled SDMA transmission within each subchannel of OFDMA. Even if the employed SDMA scheme is not as efficient as it can be, the results therein show that SDMA offers significant system throughput and QoS benefits for real time services.

Video delivery over LTE-based systems has received particular attention amongst the researchers within the last two years. In [16], the authors propose a QoS-aware OFDMA scheduling algorithm where system throughput, application QoS parameters and scheduling fairness have been jointly managed to perform radio resource allocation so that user-perceived video quality is optimized. In [17], the authors examine the performance of video applications over LTE. However, the advances of MIMO communication have not been efficiently exploited yet in video streaming applications.

In this paper, the main emphasis is to bind application (video) characteristics with efficient and low-complexity RA in MAC/PHY layers. Hence, a novel cross-layer resource allocation scheme has been proposed for video transmission over LTE-based broadband wireless systems. The interest is focused not only in quality improvement for each individual video session in terms of perceived video QoS but in improvement of the overall system performance in terms of spectral efficiency and complexity. For that reason, an integrated optimization problem is formulated that involves parameters from three layers: at the APP layer where video is encoded using AVC/H.264 standard, at the MAC layer where video packets are scheduled according to their importance and at the PHY layer where a novel linear-based SDMA algorithm is presented that supports users QoS. In general, the proposed cross-layer scheme is organized in a way where MAC functionality enforces interaction between APP and PHY layer characteristics leading, this way, to noteworthy benefits in system performance and complexity.

In Section 2, the general system framework is described. H.264/AVC and PHY/MAC characteristics of LTE are briefly described and the examined problem is specified. In Section 3, the proposed cross-layer scheme is presented, the functionality of each involved layer is analyzed and the novel SDMA algorithm is described. In Section 4, simulation setting is described and the performance of the proposed scheme is presented. Finally, conclusions and future work are drawn in Section 5.

2. SYSTEM FRAMEWORK

2.1. H.264/AVC Characteristics

H.264/AVC is one of the most widely used video coding standards in video coding. Its function is based mostly on two coordinated layers, the Video Coding Layer (VLC) that produces the coded representation of the video and Network Abstraction Layer (NAL) where the video data are encoded in a prepared way for transmission over a broad variety of systems. H.264/AVC exploits both block-based temporal and spatial prediction coding over groups of picture samples called Macroblocks (MBs). Within each picture, MBs with specific properties are organized in frames and each picture may be composed of one or several frames. The standard specifies three main types of frames depending on the encoding process: I frames, P frames and B frames. The frames of a video sequence are usually arranged in a deterministic periodic sequence of ”IBBPBBPBBPBB”, known as a Group of Pictures (GOP). The encoded video is transformed to bitstream that is organized in NAL units and Access Units (AU), where each NAL contains an integer number of bytes and each AU a number of NALs [18].

2.2. PHY and MAC Characteristics in LTE

The downlink transmission of LTE's E-UTRA is based on OFDMA. In time axis[1], the frame structure is divided in frames of 10 ms length and each frame consists of 10 subframes of duration 1 ms that can be used either for uplink/downlink transmission or control. Each subframe is consisted of two consecutive slots of equal length with slots being the smallest possible resource units in time. In the frequency axis, subcarriers have fixed bandwidth of 15 KHz. LTE's compatibility with existing wireless systems is preserved by supporting bandwidths up to 20 MHz. The smallest available resource unit (in time and frequency dimension) is called Resource Block (RB). In the most common configuration, each RB occupies one slot and $L = 12$ consecutive subcarriers [1], [2]. MIMO is an essential characteristict of LTE and multiple antennas may be used either for spatial multiplexing or transmit diversity [19]. The baseline configuration assumes a 4×2 MIMO structure with T_x= 4 antennas at Base Station (BS) and R_x=2 antennas per User Equipment. In addition to single user MIMO, multiuser beamforming and multiplexing can be supported by simultaneously transmitting to more than one users within each RB.

MAC sublayer in LTE is responsible for user scheduling, priority handling and HARQ. The data from the upper layers are organized in transport blocks and they are forwarded to physical channels. The main entity of MAC sublayer is MAC Scheduler which is responsible for running the scheduling algorithm and implementing mechanisms to meet QoS requirements (i.e. guaranteed throughput, latency etc.) by keeping an efficient balance between maximization of spectral efficiency and minimization of cost per bit. The output of MAC Scheduler is a series of transport block specifications and physical resources assignments that will be used for their transmission.

2.3. Problem Formulation

An LTE-based Downlink scenario is considered with a multiantenna BS and K single antenna users. It is assumed that each user estimates perfectly its wireless channel and feed it back instantly to the BS. Hence, the BS has perfect Channel Side Information (CSI) each time it performs user scheduling. A media server is attached to BS where a H.264/AVC-encoded video sequence is available for streaming by each one of K users. In this paper, the video encoding parameters have been predefined. Moreover, user scheduling and resource allocation are performed on fixed time scheduling periods where each period is large enough for a reasonable number of video packets to be transmitted. Finally, it is as-

[1]although LTE-TDD is considered in this paper, similar frame structure holds for FDD duplex mode too.

sumed that scheduling decisions within each scheduling period are independent from all previous and next decisions.

As it was mentioned earlier, video streaming is controlled by the system in a way that aims to effectively balance between users' QoS satisfaction level and overall (system) rate improvement. Let Q_c be the transmission set within RB c, $c = 1, \ldots, R_b$, and R_k^c be the transmission rate of user k, $k \in Q_c$, within c. In each scheduling period, the following optimization problem is formed:

$$max_{Q_c, p_{n,k}} \sum_{c=1}^{R_b} \sum_{k \in Q_c} R_k^c \; s.t. \quad (1)$$

$$|Q_c| \leq T_x, \forall c = 1, \ldots, R_b,$$

$$\sum_{n=(c-1)L+1}^{cL} \sum_{k \in Q_c} p_{n,k} \leq P_x / R_b, \forall c = 1, \ldots, R_b,$$

$$\sum_{c=1}^{R_b} R_k^c \geq \overline{R}_k, \forall k = 1, \ldots, K.$$

In the first constraint, it is ensured that mostly T_x users will share each RB since up to T_x single antenna users may simultaneously receive data when linear SDMA is employed. In the second constraint, the average power within each RB is limited where $p_{n,k}$ is the allocated transmit power of user k within subcarrier n and the total available power P_x has been equally split over the RBs. Finally, the third constraint specifies the minimum required transmission rate of users.It must be noted that each individual $\overline{R}_k$ value, $\forall k = 1, \ldots, K$, depends on both the encoded video characteristics and the targeted QoS. Given the length of the scheduling period T_p, video traffic load (in bytes) can be directly transformed to guaranteed QoS in terms of transmission rate.

The problem of eq. (1) is difficult to be solved since it is not in convex form. Moreover, its optimal solution leads to non-linear transmission techniques with high and unpractical complexity. Thus, the interest is focused on suboptimal solutions which are characterized by both high-efficiency and low-complexity. Such a cross-layer solution is described in the following section and binds H.264/AVC characteristics with an efficient Zero Forcing Beamforming (ZFB) based and low-complexity user scheduling in MAC/PHY layers.

When ZFB is performed within each RB c, $c = 1, \ldots, R_b$, the normalized vectors $\mathbf{w}_{n,k} = [w_{n,k,1} \ldots w_{n,k,T_x}]^T, \forall n = (c-1)L+1, \ldots, cL$, map the signal of user $k \in Q_c$ to T_x transmit antennas. The general transmission model within c is

$$\mathbf{y}_n = \mathbf{H}_n \mathbf{W}_n \mathbf{s}_n + \mathbf{z}_n, \;\; n = (c-1)L+1, \ldots, cL, \quad (2)$$

where the vector $\mathbf{y}_n = [y_{n,1} \ldots \; y_{n,|Q_c|}]^T \in \mathbb{C}^{|Q_c| \times 1}$ contains all the received signals within subcarrier n, $\mathbf{x}_n = \mathbf{W}_n \mathbf{s}_n \in \mathbb{C}^{T_x \times 1}$ is the transmitted signal in subcarrier n, $\mathbf{H}_n \in \mathbb{C}^{Q_c \times |T_x|}$ is the matrix of channels $\forall k \in Q_c$ and $\mathbf{W}_n \in \mathbb{C}^{T_x \times |Q_c|}$ is the corresponding beamforming matrix. The uncorrelated entries of $\mathbf{s}_n \in \mathbb{R}^{Q_c \times 1}$ contain the symbols destined to users in Q_c and $\mathbf{z}_n = [z_{n,1} \ldots \; z_{n,|Q_c|}]^T \in \mathbb{C}^{|Q_c| \times 1}$ denotes the $|Q_c|$ i.i.d. samples of circularly symmetric complex Gaussian additive noise with zero mean and p.s.d. N_0. In ZFB, zero interference condition is satisfied within each subcarrier of the RB c, meaning $\mathbf{h}_{n,k}^T \mathbf{w}_{n,j} = 0$ for every two different users k and j which transmit simultaneously within c. Thus, the total beamforming matrix within subcarrier n is $\mathbf{W}_n = \mathbf{H}_n^{\dagger} (\mathbf{H}_n \mathbf{H}_n^{\dagger})^{-1}$ and the transmission rate of each $k \in Q_c$ is

$$R_k^c = \sum_{n=(c-1)L+1}^{cL} \underbrace{\Delta_f \log_2 (1 + \frac{\left\| \mathbf{h}_{n,k}^T \mathbf{w}_{n,k} \right\|^2 p_{n,k}}{\Delta_f N_0})}_{R_{k,n}} \quad (3)$$

where Δ_f is subcarrier's bandwidth and $R_{k,n}$ is the transmission rate of user k within subcarrier n, $n = (c-1)L + 1, \ldots, cL$ [20].

3. CROSS-LAYER SCHEME

3.1. Cross-Layer Approach

In the following, the considered video sequence is comprised only of I and P frames. NALs from each stream are encapsulated in RTP/IP packets and are sent to the MAC Layer where they are served in FIFO order. Clearly, for each user, I-packets are more important than P-packets since the loss of an I-packet may lead to error propagation within the GoP. Hence, packet scheduling in MAC layer is adapted to H.264/AVC nature by prioritizing I-packets against P-packets for each stream [21]. However, it should be noted that video quality is heavily degraded too in the case where many P-packets are lost.

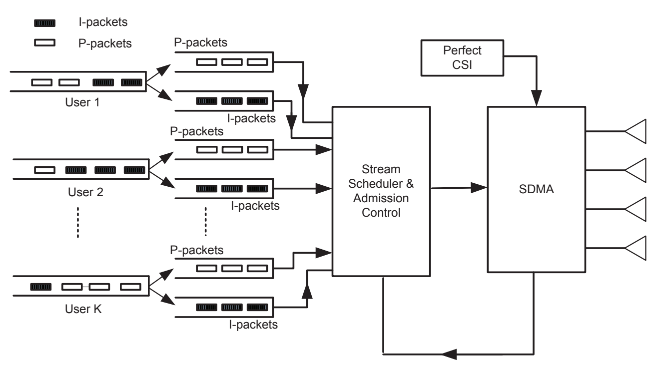

Fig. 1. Functionality of MAC Scheduler.

In Fig. 1, the MAC scheduler functionality of the proposed cross-layer scheme is depicted. Two separated virtual packet queues are established per streaming user that collect I-packets and P-packets of all transmitted frames, respectively. Clearly, in eq. (1) a total rate constraint is specified per user. Thus, the value of T_p determines jointly the service rate requirements of both I-packet and P-packet virtual queues. However, the different rate requirements of each user I-packet and P-packet streams (that they are imposed by H.264/AVC) can be serviced by the appropriate coordination between the two virtual queues. More specifically, within each scheduling period, each user's I-packet transmission precedes that of P-packet. This way, transmission of future I-packets, within either the current or the following GoPs, may occur prior to the transmission of P-packets from the current GoP.

The proposed functionality of MAC Scheduler advantages on a twofold way versus a conventional approach where video packets are scheduled sequentially: Firstly, I-packet traffic of each user is served continuously as long as $\overline{R}_k$ has a valued that supports the corresponding traffic load. This is very important since loss of I-packets degrades heavily the H.264/AVC-encoded video quality. Secondly, a flexible balance is provided between user QoS and overall system performance (in terms of system throughput) that can be dynamically tuned w.r.t. system condition, wireless channels quality, users priorities etc.

3.2. Resource Allocation in PHY/MAC Layers

In this subsection, the user scheduling and SDMA approach previously presented in [20] is extended to take into account user's transmission rate requirements. In general, the proposed algorithm aims to form sets of users with as much as possible compatible wireless channels (low average spatial correlation) since for this kind of sets high sum rate and individual rates can be achieved at the same time. Moreover, the inherent inter-subcarrier correlation within each RB is exploited by specifying each set Q_c, $c = 1, \ldots, R_b$, based on the channel conditions within the middle subcarrier of c. This is highly efficient when coherence bandwidth is larger than the bandwidth of the RB and decreases effectively the complexity of the user scheduling process. The description of the proposed algorithm follows:

Let $\mathcal{U} = \{1, \ldots K\}$ denotes the set of all K users and $\mathcal{U}_P$ the set of users that have not satisfied yet their overall transmission rate (initially $\mathcal{U}_P = \mathcal{U}$). Moreover,let n^m be the middle subcarrier of each RB. Initially, $Q_c = \oslash$, $\forall c = 1, \ldots, R_b$. For each RB $c = 1, \ldots, R_b$, the following steps are performed:

A. *First User Selection:*

- The first user is $k_c^* = \arg\max_{k \in \mathcal{U}_P} R_{k,n^m}$. If such a user doesn't exist, then $k_c^* = \arg\max_{k \in \mathcal{U}} R_{k,n^m}$.
- The sum rate within c is set equal to $R^c_{k_c^*}$ and $Q_c = \{k_c^*\}$.

B. *User Set Completion:* While $|Q_c| < T_x$, the following steps are performed within RB c.

(a) The average spatial correlation among already selected users and each candidate $k \in \mathcal{U} \setminus Q_c$ is computed as $\frac{\sum_{i \in Q_c} \rho^{n^m}_{i,k}}{|Q_c|}$ and a set of cardinality M^2 is formed that contains the users with the smallest average spatial correlation values.

(b) Each member of the above mentioned set is temporarily added to Q_c and the new achieved RB's sum rate is computed via waterfilling on the effective channels [20]. The member of the set that leads to the maximum new sum rate is permanently added to Q_c, if the sum rate of the RB is increased. In such a case, the sum rate of the RB and Q_c are renewed accordingly and the step B) is repeated (if $|Q_c|$ becomes T_x, each of the selected users $k \in Q_c$ that gets overall sum rate higher than $\overline{R}_k$ is removed from $\mathcal{U}_P$). Otherwise, the set Q_c is finalized (again, the users in Q_c that gets overall sum rate higher than $\overline{R}_k$ are removed from $\mathcal{U}_P$) and the process is continued with the next RB (if any).

The normalized spatial correlation between users i and j within subcarrier n is given by $\rho^n_{i,j} = \frac{\left\|\mathbf{h}^{\dagger}_{n,i}\mathbf{h}_{n,j}\right\|}{\|\mathbf{h}_{n,i}\|\|\mathbf{h}_{n,j}\|}, 0 \leq \rho^n_{i,j} \leq 1$. Generally, as lower as $\rho^n_{i,j}$ is more efficiently users i and j can be combined within subcarrier n. In the proposed scheme, each set Q_c is gradually built up by forcing the first selected user to be one that has not satisfied yet its rate requirement (as long as such one exists). Thus, transmission rate constraints of the users with poor channel conditions can be fulfilled too. Beyond this, the available space and power resources are allocated in order to maximize the overall system throughput. For that reason, each time Q_c is augmented (up to cardinality T_x), a user with low average spatial correlation with the already selected ones is included, as long as a new insertion improves the overall sum rate. Moreover, power allocation across users within Q_c is performed by waterfilling on the effective channels [20]. It can be easily shown, that the asymptotic complexity of the proposed scheme is $\mathcal{O}\left(R_b L K T_x^2\right)$.

4. NUMERICAL RESULTS

In this section simulation results are presented to illustrate the performance of the proposed cross-layer scheme. The general system parameters are shown in Table 1. In PHY layer, only small scale fading is considered where the inter-subcarrier correlation between subcarriers m and n is described by $r_{m,n} = 1/\sqrt{1 + \left(\frac{2(m-n)\Delta_f}{B_{coh}}\right)^2}$ $m, n = 1, \ldots, N$.

[2] in simulation results M is equal to T_x

In APP layer, a synchronized homogeneous case is considered where all the users are interested for the same video sequence and streaming synchronization is performed every 300 frames. The overall transmission rate constraint (I-packets and P-packets) for each video streaming user is 1.2 Mbps which is high enough for the video sequence 'Fish' (retrieved from [22]) that has been encoded using the parameters shown in Table 1. All simulation results are averaged over 5000 realizations.

Table 1. System and Video Encoding Parameters

Quantity	**Value**
Time Transmission Interval (T_p)	250ms
Number of Resource Blocks (R_b)	50
Subcarrier Spacing (Δ_f)	15 KHz
BS Power (P_x)	20 W
Coherence Bandwidth (B_{coh})	300 KHz
Video Duration	1080 frames
Frame Rate	30fps
GoP Size	12 ($IPP \dots P$)
Average Size of I-Frame	7242 bytes
Average Size of P-Frame	3665 bytes
Average NALs per I-Frame	7.54 packets
Average NAL per P-Frame	4.05 packets

In Fig. 2, the throughput of the proposed cross-layer scheme versus the number of active video sessions is shown for average SNR equal to 10dB and 20 dB. Moreover, the performance of two other RB allocation policies is illustrated where the same MAC scheduling has been used (for comparison reasons). In the first one, transmission to only one user is allowed within each RB using Maximum Transmission Ratio (MTR). In the second one, the SDMA approach of [15] is employed.

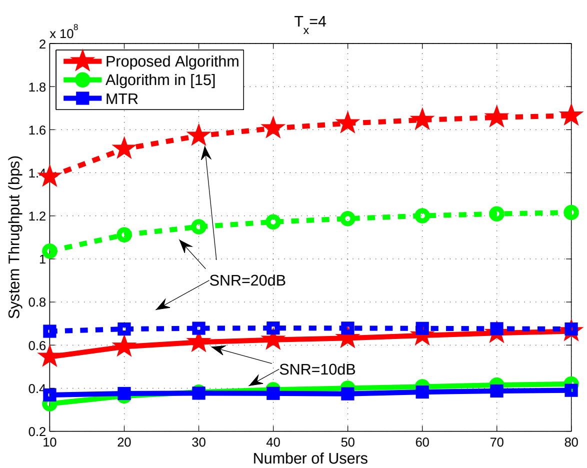

Fig. 2. Sum Rate Vs Number of Users.

As can be seen, the proposed scheme shows better system performance than the other two policies for both medium and high SNR values. Single user transmission using MTR does not fully exploit all the multiuser diversity of the system. Lack in performance of the approach in [15] springs from the fact that used SDMA doesn't assess spatial compatibility of simultaneously transmitting users within each RB. This is important in the area of low to medium SNRs where SDMA in [15] doesn't offer any significant benefit over MRT [23].

Table 2. Average Perceived Video Quality for the Three Cross-Layer Schemes (SNR=10dB)

No of Users	MTR	Scheme in [15]	Proposed Scheme
10	38.36	38.36	38.36
20	38.36	38.36	38.36
30	33.59	33.14	38.36
40	26.28	26.46	38.36
50	20.83	21.17	33.52
60	20.49	20.59	27.18

In Table 2, the average perceived video quality of one video user is illustrated against the different cross-layer schemes. The proposed scheme outer-performs against the other two schemes by leading to significant higher perceived video quality. This is due to the fact that a higher system throughput is offered and a larger number of users can be simultaneously supported with adequate transmission rates provided to each individual one. Thus, the packet error rate due to physical constraints is lower when efficient SDMA in PHY/MAC layer is combined with packet scheduling by taking into account video streaming applications' semantics. This is evident in Fig. 3 where the PSNR over time is illustrated for all cross-layer schemes when the number of users equals to 50.

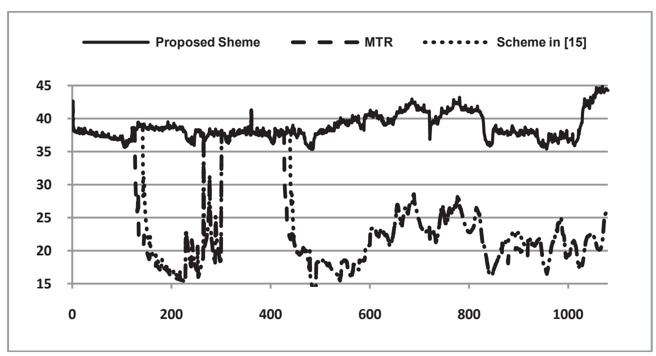

Fig. 3. PSNR Video Quality Comparison (No of Users: 50, SNR=10dB).

5. CONCLUSIONS AND FUTURE WORK

In this paper a cross-layer solution has been presented for video transmission over LTE-based broadband systems. The proposed cross-layer scheme considers user/stream scheduling for synchronized, real time, video traffic by taking into account parameters from Application, MAC and Physical Layer. These parameters are combined within a novel RA algorithm at the Physical Layer with rate transmission guarantees. Simulations results have shown that the proposed cross-layer scheme is characterized by high performance in terms of system throughput and perceived QoS and outperforms against similar cross-layer schemes. Future work includes extension of the proposed cross-layer design to more realistic scenarios w.r.t LTE's characteristics, heterogeneous video characteristics, traffic requirements, etc.

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