Spectrum-aware Radio Resource Management for Scalable Video Multicast in LTE-Advanced Systems

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***Abstract*—In this paper, we consider scalable video multicast to LTE-A user groups. We focus on the problem in accommodating the varying channel conditions amongst group members to adaptively select modulation schemes that meet the desired QoS objectives for the bitstream layers. We envision a fair provisioning of the base layer to ensure baseline quality to all users and an opportunistic provisioning of the enhancement layers to maximize system utility. We show NP-Hardness in the formulation of the base and enhancement layer resource allocation to the groups and design greedy approximations to solve them. Further, this paper discusses a scheduling mechanism to handle contention of resources amongst groups. We developed and integrated a carrier aggregation module in network simulator NS3 to conduct extensive simulations. In different scenarios, we demonstrate improvements in terms of achieved base and enhancement layer throughputs, net downlink LTE-A throughput and satisfiability of the groups.**

I. Introduction

LTE-Advanced (LTE-A) targets high data rates of 500 Mbps in uplink and 1 Gbps in downlink for low speed mobile User Equipments (UEs), with video being a data-hog in such high-speed networks. It also provisions for Enhanced Multimedia Broadcast/Multicast Services (eMBMS) which provide dedicated downlink resources for video multicast scenarios. There has been increasing interest and research in provisioning these resources optimally to the UEs, recognizing the potential of multicast services to cater to a large group of users watching live-video streaming events to enhance their viewing experience. LTE-A provisions for Carrier Aggregation (CA) which allows integrating contiguous or non-contiguous carriers at the base station, the LTE Evolved Node B (eNB), so as to provision a peak bandwidth of 100 MHz. The Radio Resource Management (RRM) framework of a multi-carrier LTE-A system comprises the Component Carrier (CC) Assignment and scheduling functionalities of the Evolved-Node B (eNB or base station) [1].

The encoding of a high-quality video bitstream into one or more subset bitstreams by exploiting the correlation between the subsets, coded at different operating points, is standardized by Scalable Video Coding (H.264 SVC). Video is encoded at different layers. The lowest layer, i.e. Layer 0, is called the base layer and has the least quality. A number of enhancement layers can be coded (1,2,3) to provide different quality guarantees. An enhancement layer (say 3) can be decoded only if the base layer and lower enhancement layers (1 and 2) are also received by the UE.

It becomes increasingly important to provision high quality video delivery in multicast groups. UEs within the same group could be geographically distant as some having good channel conditions while others are starving for channel resources lying in cell edge or other higher interference zones. Typically, the quality of video received by members of a group is limited by the weakest link from any UE within the group to the eNB. However, the challenge in multicasting scalable layers is ensuring a minimum satisfactory quality to every user in the cell while maximizing the average user's experience as a whole.

In this paper, we consider low-speed LTE-A UEs within a cell range subscribing to multicast services. Based on shared viewing interests, they form multicast groups. A Single Cell Point-To-Multipoint (SCPTM) scenario is envisioned in our paper. eMBMS p-t-m transmissions are used to transfer MBMS specific control/user plane information from the eNB to a group of UEs over shared resources. The functionalities such as packet scheduling, link adaptation, adaptive modulation and coding and Hybrid Automatic Repeat reQuest (HARQ) are performed with respect to each group of eMBMS subscribers. We consider transmission of scalable HD videos over eMBMS, identify the challenges in optimal perceptual delivery to end users and propose independent service objectives for the base and enhancement layers. Further, it shows NP Hardness in the formulation for allocating resources to multicast groups to independently provision the base and enhancement layers and proposes near-optimal greedy approximation heuristics with fairness objective for the base layer and opportunistic objective for the enhancement layer. We use H.264 SVC scalable codec (JSVM reference implementation) to evaluate the perceptual video quality. The main features of our proposed approach are as follows:

1) *Good CCs* - A designation of *assignable* resources in the aggregated carrier for the base layer, as in Section III.
2) *Fair assignment* of carriers for base layers to ensure all users in group get a baseline viewing experience, as in Sections III and IV-A.
3) *Opportunistic assignment* of carriers for enhancement layer to ensure that aggregated throughput of group (and hence viewing experience) is maximized, as in Sections III and IV-B.
4) Higher *group satisfaction* by handling resource contention amongst groups, as in Section IV-C.

II. Review of Existing Literature

Carrier Aggregation and Scheduling: Several research efforts involving Carrier Aggregation have been reported recently. In [2], a cross-CC Proportional Fair Packet Scheduling (PFPS) is proposed to improve the coverage, performance of the system and enhance the fairness in allocating resources to the UEs.The authors use the traditional Proportional Fair Packet Scheduling (PFPS) mechanism [3] in which any PRB of a CC is allocated to the UE, based on the instantaneous achievable throughput and the past achieved throughput. The CC assignment is channel-blind and varying traffic requirements of the UEs are not considered. Inter-band CA, aggregating CCs from non-adjacent frequency bands is discussed in [4], [5]. In [4], as the UEs could not be scheduled on every CC due to path loss variations, the authors form groups of UEs based on spatial channel modeling, and propose a modified UE group-based PFPS. In [5], additionally, the notions of primary cell and secondary cells are also discussed. In [6], the authors extensively discuss Maximum Throughput, Proportional Fair,Blind Equal Throughput scheduling techniques, which are extensively used in our performance evaluation from the context of scheduling eMBMS groups.

eMBMS in LTE: In [7], the authors discuss p-t-m transmission mechanism for MBMS services in High Speed Data Packet Access (HSDPA) downlink, standardized in 3GPP Release 6. The authors discuss two link adaptation-based algorithms for reducing the number of HARQ re-transmissions, which are critical to multicast downlink throughput, based on UE-reported feedback. We give significant consideration to this issue from the context of RRM for the base layers of the subscribed videos. Channel-aware Frequency Domain Packet Scheduling (FDPS) is proposed in [8], which is one of the first works contributing towards scheduling of eMBMS groups. The proposed mechanism in this paper selects a PRB for the user whose worst estimated throughput on that PRB, when compared to other PRBs, is the highest in the group. When this degree of fairness seems reasonable to accommodate the weakest terminal, it would be applicable only for the base layers. For a higher perceptual video quality, a higher number of enhancement layers are required. But, this mechanism limits the number of enhancement layers due to a very high degree of fairness for the weakest terminals.

Scalable video coding in cellular networks: In [9], the authors propose a two-step dynamic programming algorithm to choose appropriate Modulation and Coding Scheme (MCS) for each video layer and determine the optimal resource allocation amongst multiple video sessions. In [10], the authors select the appropriate substream of scalable video layers to WiMAX users with limited energy resources within the scheduling window's capacity constraints to increase the Peak Signal to Noise Ratio of the selected substream. They claim to maximize the video quality and minimize the energy consumption for mobile receivers. They model the problem theoretically as an NP-Complete 0-1 Multiple Choice Knapsack Problem. However, this work does not account for accommodating the frequency diversity among an eMBMS group for scheduling purposes.

III. Problem Formulation and System Model

The cell structure considered in our paper consists of uniformly-distributed LTE-A UEs. Two or more UEs, subscribing to a common multimedia service, join a multicast session, forming an eMBMS group. This subscribed multimedia application is encoded using Scalable Video Coding (SVC), generating a base layer and several enhancement layers. We set the following QoS objectives for an optimized video delivery by the service provider:

- Every group should successfully decode the base layer of each subscribed multimedia traffic.
- The perceptual quality of the received video by the group should be of maximum quality with as many enhancement layers as possible.

From the above QoS objectives, the base layer bit rate requirements of any subscribed traffic is termed as its Guaranteed Bit Rate (GBR) and the bit rate requirements of each of the enhancement layers sum up to its Maximum Bit Rate (MBR). With more than one subscribed application, the sum of its GBR traffic rates is termed as the Aggregate GBR (AGBR) and the sum of its MBR rates is the Aggregate MBR (AMBR).

A. *Resource Allocation for Base and Enhancement Layers*

To enable base layer decodeability by all the groups and to maximize the number of enhancement layers for a higher downlink throughput, the base layer should be provisioned over a *minimum* possible number of PRBs in any given subframe, as formulated in Eqn. 1 below:

$$\begin{aligned}&\text{Minimize } V = \sum_{i=1}^{N} \left|\mathfrak{W}_i^b\right| \text{ where } \mathfrak{W}_i^b \subseteq \mathfrak{V}\\&\text{subject to } \sum_{v\in\mathfrak{W}_i^b} \left(\beta_v \times \gamma_{v,i}^b\right) \geq R_i^b, \forall G_i \in \mathfrak{G}\\&\text{where } \gamma_{v,i}^b = \min\{\bigcup_{r\in G_i} \overline{\gamma_{v,r}}\}\end{aligned} \quad (1)$$

where N is the number of eMBMS groups in the cell, $\mathfrak{W}_i^b$ is the set of PRBs allocated to group G_i for the base layer out of the comprehensive set of PRBs, $\mathfrak{V}$, of the aggregated carrier, $\mathfrak{G}$ is the set of groups, β_v is the bandwidth of the v^{th} PRB, $\gamma_{v,i}^b$ is the spectral efficiency chosen for the v^{th} PRB on group G_i for provisioning the base layer, R_i^b is the base layer bit rate, required by the scalable video traffic application(s), subscribed by the group G_i and $\overline{\gamma_{v,r}}$ is the spectral efficiency reported by any individual UE r from group G_i on PRB v. As the base layer should be decoded by all the UEs in any group G_i, the MCS level to be used on any PRB v meant to serve the base layer for G_i should be the least value of the MCS estimated for any UE r from G_i on v. Hence, $\gamma_{v,i}^b$ is the minimum value in the set of spectral efficiencies reported by every UE $r \in G_i$ over PRB v. When the base layer bandwidth requirements of any group G_i are met using the *minimum* possible number of PRBs from the aggregated carrier, the number of groups being simultaneously served by CC assignment, without any mutual resource contention, would be the largest possible. This results in satisfying the base layer decodeability for each group.

Provisioning the enhancement layers is optional, unlike the base layer, however recommended. A *best-effort* resource allocation strategy is chosen by which the number of enhancement layers and the per-layer aggregated throughput, defined as the product of the throughput and the fraction of the total number of users in the group that could achieve it, are maximized.

$$\begin{aligned} &\text{Maximize } \sum_{l=1}^{L^\star}\sum_{i=1}^{N}\left(\beta_v \times \gamma_{v,i}^{\text{enh}} \times \frac{U_i^{\gamma_{v,i}^{\text{enh}}}}{|G_i|}\right) \text{ , } \forall v \in \mathfrak{W}^l \\ &\text{subject to } \sum_{v\in\mathfrak{W}_i^l}\left(\beta_v \times \gamma_{v,i}^{\text{enh}}\right) \geq R_i^l \text{ , for } i = 1, 2, \ldots N \\ &\text{and } l \leq L^\star \leq L \end{aligned} \tag{2}$$

where L is the given total number of enhancement layers, $L^\star$ is the *optimal* number of enhancement layers achieved, $\beta_v \times \gamma_{v,i}^{\text{enh}} \times \frac{U_i^{\gamma_{v,i}^{\text{enh}}}}{|G_i|}$ is the aggregated throughput of G_i over PRB v, $\gamma_{v,i}^{\text{enh}}$ is the spectral efficiency chosen for the v^{th} PRB on group G_i to provision an enhancement layer, $U_i^{\gamma_{v,i}^{\text{enh}}}$ is the number of UEs from G_i supporting $\gamma_{v,i}^{\text{enh}}$, $\mathfrak{R}_i$ is the MBR of the traffic subscribed by G_i and $R_i^l = \frac{\mathfrak{R}_i - R_i^b}{L}$ is the bit rate required for enhancement layer l, as detailed in Section IV-B2. Higher the number of enhancement layers provisioned and higher the number of eMBMS groups served will help maximizing the net enhancement layer throughput. So, it is required to provision the l^{th} enhancement layer in adequate number of PRBs. Secondly, as a *best-effort* service is adopted for enhancement layers, it is not required for every UE in the group to successfully decode the layers and so, the spectral efficiency constraint in Eqn. 1 for the base layers is relaxed here.

B. Designation of assignable resources

Non-adjacent inter-band CCs with different central band frequencies are considered for CA [1], [5] and allocation of resources to the UE groups. The log-distance path loss computation (in dB) for a CC x with central-band frequency f_x (in MHz) for any UE r at a distance d_r (in km) is as follows [1], [4]:

$$PL_{r,x}(dB) = \alpha \log_{10}(f_x) + \vartheta \log_{10}(d_r) + c_r \tag{3}$$

where, α and ϑ are constants that represent path loss exponents. c_r is a normally-distributed random variable, representing the shadowing effect, with zero mean and standard deviation σ, ranging from 3 dB to 10 dB. To determine eMBMS groups with largely poor channel qualities (i.e. groups where most of the UEs have a higher path loss with most of the CCs), we set a path loss threshold PL_{th}. The CCs in the aggregated carrier whose path loss values with respect to a given UE are less than a pre-defined threshold are distinguished as *good* CCs for the UE from the rest of the CCs in the aggregated carrier. Now, let us determine the probability, $\Pr(GC_{x,r})$, that the given CC x is a *good* CC for the UE r.

$$\begin{aligned} &\Pr(GC_{x,r}) = \Pr(PL_{r,x} \leq PL_{Th}) \\ &= \Pr((\alpha \log_{10}(f_x) + \vartheta \log_{10}(d_r) + c_r) \leq PL_{Th}) \\ &= \Pr(\log_{10}(d_r) \leq \frac{1}{\vartheta}(PL_{Th} - (c_r + \log_{10}(f_x^\alpha))) \\ &\Rightarrow \Pr(GC_{x,r}) = \Pr(d_r \leq \frac{10^{\frac{PL_{Th}-c_r}{\vartheta}}}{f_x^{\frac{\alpha}{\vartheta}}}) \equiv \Pr(d_r \leq D_x) \\ &\text{where } D_x = \frac{10^{\frac{PL_{Th}-c_r}{\vartheta}}}{f_x^{\frac{\alpha}{\vartheta}}} \end{aligned} \tag{4}$$

Considering the uniform distribution of UEs within the cell and the normally-distributed random variable c_r for shadowing, we have:

$$\begin{aligned} \Pr(d_r \leq D_x|c_r) &= \int_{q=0}^{D_x} \frac{2\pi q}{\pi D_{eq}^2} \mathrm{d}q = \frac{2}{D_{eq}^2}\left(\frac{D_x^2}{2}\right) \\ &= \frac{1.2076}{D^2}\left(\frac{100^{\frac{PL_{Th}-c_r}{\vartheta}}}{f_x^{2\frac{\alpha}{\vartheta}}}\right) \end{aligned} \tag{5}$$

where, D_{eq} is the radius of the circle, approximated from the hexagonal cell of radius D, as cited in [11], where $D_{eq} = \sqrt{\frac{3\sqrt{3}}{2\pi}}D = 0.91D$. With ξ_0 and ξ_1 being the limits of the shadowing random variable c_r with respect to the given propagation scenario (say, indoor urban, outdoor, freeway, etc.), we have:

$$\begin{aligned} &\Pr(d_r \leq D_x) = \int_{c=\xi_0}^{\xi_1} \frac{1.2076}{D^2}\left(\frac{100^{\frac{PL_{Th}-c}{\vartheta}}}{f_x^{2\frac{\alpha}{\vartheta}}}\right) \frac{e^{-\frac{(c-\mu)^2}{2\sigma^2}}}{\sigma\sqrt{2\pi}} \mathrm{d}c \\ &= \frac{1.2K}{D^2}\left(\frac{100^{\frac{PL_{Th}}{\vartheta}}}{\sigma\sqrt{2\pi}f_x^{2\frac{\alpha}{\vartheta}}}\right)\left|\text{erf}\left(\frac{\sigma^2\log(100) - \vartheta(\mu - c)}{\vartheta\sigma\sqrt{2}}\right)\right|_{c=\xi_0}^{\xi_1} \\ &\text{where } K = \sigma\sqrt{\pi}.2^{-\left(\frac{4\mu+\vartheta}{2\vartheta}\right)}25^{-\frac{\mu}{\vartheta}}e^{\frac{\sigma^2\log^2(100)}{2(\vartheta)^2}} \text{ is a constant.} \end{aligned} \tag{6}$$

In general, the probability that the CC x with central band frequency f_x is a *good* CC for the UE r is given by:

$$\Pr\{GC_{x,r}\} = \Pr\{d_r \leq D_x\} \propto \frac{1}{f_x^{2\frac{\alpha}{\vartheta}}} \tag{7}$$

Thus, the probability of a CC being a *good CC* is a function of the square of f_x alone. Let $\Pr(GC_{a,r})$ and $\Pr(GC_{b,r})$ be the probabilities that the CCs with central band frequencies f_a and f_b respectively are *good* CCs to the UE r. Then, if CC with central band frequency f_b is a *good* CC to the UE, then CC with central band frequency f_a will also be a *good* CC to the UE, if and only if $f_b > f_a$ due to higher path loss values for CCs with higher central band frequencies. So, $\Pr\{GC_{a,r}|GC_{b,r}\} = 1$ and thus,

$$\Pr\{GC_{a,r} \bigcap GC_{b,r}\} = \Pr\{GC_{b,r}\} \propto \frac{1}{f_b^{2\frac{\alpha}{\vartheta}}}$$

In general, the probability that any UE r has j *good CCs* is limited by the highest central band frequency among the CCs.

$$\Pr\{GC_{a,r} \bigcap GC_{b,r} \bigcap ...GC_{j,r}\} = \Pr\{GC_{j,r}\} \propto \frac{1}{f_j^{2\frac{\alpha}{\vartheta}}} \tag{8}$$

where, $\Pr\{GC_{a,r} \bigcap GC_{b,r} \bigcap ... \bigcap GC_{j,r}\}$ is the probability that there are j *good* CCs for UE r or the PDF of the number of *good* CCs in the aggregated carrier for the UE r.

IV. Resource Allocation

This section discusses assigning the PRBs of the CCs in the aggregated carrier to the eMBMS groups for provisioning the base and enhancement layers of the subscribed videos.

A. For the base layer

As it is required to guarantee the mandatory base layers to all the groups, the PRBs for provisioning the base layer of the subscribed multimedia traffic are allocated to each group before moving on to the enhancement layers.

1) Problem Hardness: : Resource allocation for the base layer, as described in Eqn. 1 of Section III, is equivalent to a variant of the *NP- Complete Generalized Assignment* problem (GAP) [12], stated as follows with representative terms mentioned in braces: Given a set of items (groups $\{G_1, G_2, \ldots G_N\}$) with resource requirement values (base layer bit rate requirements $\{R_1^b, R_2^b, \ldots R_N^b\}$) and a set of resources (PRB set in the aggregated carrier $\mathfrak{V}$), such that each resource (PRB $v \in \mathfrak{V}$) has a weight (bandwidth β_v) and an allocation value, (spectral efficiency $\gamma_{v,i}^b$), with respect to any item G_i, determine the subset of resources to be allocated for each item G_i (PRB set $\mathfrak{W}_i^b \in \mathfrak{V}$) such that each item's resource requirements are atleast satisfied by the net value of the assigned resources, i.e. $\sum_{v \in \mathfrak{W}_i^b} \left(\beta_v * \gamma_{v,i}^b\right) \geq R_i^b$, for all $i = 1, 2, \ldots N$. A solution is *optimal* if the requirements of all the items G_1 to G_N are satisfied using the *minimum* possible number of resources, i.e. $V = \sum_{i=1}^{N} \left|\mathfrak{W}_i^b\right|$ is *minimum*. The GAP is thus reduced to the base layer resource allocation problem in polynomial time. In other words, the base layer resource allocation for the eMBMS groups is an *NP-Hard problem*. Greedy approximation algorithms are generally used to solve the GAP by determining the local *optimum* solution at each stage with the aim of finding a global *optimum*. An important strategy in doing this involves sorting the items efficiently and iterating across each item in sorted order towards determining the global *optimum*. Analogically, the groups are ordered as in Section IV-A2.

2) PRB Allocation: : If the base layer bit rate requirements of any group G_i have to be satisfied using the *minimum* number of PRBs (forming a set $\mathfrak{W}_i^b$), the spectral efficiency $\gamma_{v,i}^b$ has to be maximum on each of its selected PRB v, which indicates that the chosen Modulation and Coding Scheme (MCS) for the PRB v must be maximum. The Signal-to-Noise Ratio (SNR) for any UE r on any sub-carrier s of the CC with central band frequency f_x and an eNB's transmitting power of P, with non-interfering eNBs, is given by [13]:

$$SNR_{s,r} = \frac{\frac{P}{PL_{r,x}} . y_s}{N_0} \tag{9}$$

where N_0 is the spectral noise and y_s is a random variable for fast-fading, specific to sub-carrier s with PDF $p_{y_s}(y_c) = e^{-y_c}$. The SNR for a PRB v, its Channel Quality Indicator (CQI) and MCS are determined as in [14], [15]. Let $M_{v,r}$ be the number of bits transmitted per symbol corresponding to the chosen MCS index for PRB v and let $e_{v,r}^c$ denote the coding rate, corresponding to this MCS. The spectral efficiency for sub-carrier v in *bps/Hz* with respect to r is given by: $\overline{\gamma_{v,r}} = M_{v,r}.e_{v,r}^c.(1 - BLER_{v,r})$, where $BLER_{v,r}$ is the BLock Error Rate, with a value less than 10% (as accepted in LTE). From the spectral efficiency of the PRB v, its effective SNR for a UE r can be defined as : $SNR_{v,r} = 2^{\overline{\gamma_{v,r}}} - 1$.

In an eMBMS scenario, for a given sub-frame, each UE from any group G_i is allocated onto the same set of PRBs in the aggregated carrier. So in order to achieve a higher spectral efficiency for any group G_i, it is required to allocate the group with the PRBs of the CC having a lower path loss in the aggregated carrier. In other words, PRBs from the *good* CCs of group G_i must be allocated to the group. As the same set of PRBs cannot be allocated to more than one eMBMS group simultaneously, it is required to prioritize the groups for the allocation of frequency resources. From Eqns. 6 and 8, we infer that:

- The probability that a given CC is a *good* CC for a group is higher when its central-band frequency is lower.
- The probability for a group to have a larger number of *good* CCs is higher when the UE, farthest from the eNB in the group, is closer to the eNB.

As the base layers of the subscribed multimedia traffic applications should be made decodeable to all the UEs within any group, the set of CCs, considered for assignment to serve the base layers for the group G_i, is the common set of *good* CCs of all the UEs in the group, termed as *common good* CCs. It is given by:

$$\zeta_i = \bigcap_{r \in G_i} \omega_r \tag{10}$$

where ω_r is the set of *good* CCs in the aggregated carrier for any UE r. We then assign a priority metric ρ_i^b to G_i.

$$\rho_i^b = c.\left(\frac{1}{|\zeta_i|}\right) \tag{11}$$

If for any two groups G_i and G_j, if $\rho_i^b = \rho_j^b$, then the priority metric for G_i is given by:

$$\rho_i^b = a.\left(R_i^b\right) \tag{12}$$

where, R_i^b is the AGBR of G_i and c and a are proportionality constants. The aggregated carrier comprises CCs sorted in increasing order of their central-band frequencies. The algorithm for assigning the PRBs of the CCs belonging to the aggregated carrier for the eMBMS groups is outlined in Alg. 1.

3) Analysis: The proof of correctness for the near-optimal prioritization of the eMBMS groups, by the greedy heuristic discussed above, for base layer resource allocation follows the proof detailed in Section IV from [1], which infers that even if the groups with the largest number of *common good* CCs is least-prioritized for Base Layer resource allocation, they would still be assigned on to the PRBs from their *common*

Algorithm 1 PRB assignment for Base Layer

1: *Begin Proc*{*PRB Assignment*}
2: Sort the groups in non-increasing order of their priority metric ρ_i^b, forming a set $\mathfrak{G}_b$
3: Sort the aggregated carrier $\mathfrak{V}$ with CCs in increasing order of their central-band frequencies
4: **for** each group G_i in $\mathfrak{G}_b$ **do**
5: Set $\mathfrak{W}_i^b := \{\emptyset\}$
6: **while** $R_i^b \neq 0$ **do**
7: Set $v := \arg\max_v \{\bigcup_{v \in \zeta_i} \gamma_{v,i}\}$
8: Set $R_i^b := R_i^b - \gamma_{v,i}.\beta_v$ and $\mathfrak{W}_i^b = \mathfrak{W}_i^b \bigcup \{v\}$
9: Set $\mathfrak{V} := \mathfrak{V} - \{v\}$
10: **end while**
11: **if** $R_i^b \neq 0$ **then**
12: Set $\mathfrak{G}_b := \mathfrak{G}_b - \{G_i\}$
13: **end if**
14: **end for**
15: *End Proc*{*PRB assignment*}

good CCs, while preventing resource exhaustion for those with the least number of *common good* CCs. Thus, this ensures a near-optimal prioritization with a higher probability of base layer decodeability by each group.

We now derive the lower and upper bounds of our proposed *near-optimal* solution. Let $V^\star$ be the optimal number of allocated PRBs, out of which $\mathfrak{W}_i^b\star$ is the PRB set allocated to G_i for the base layer.

$$\begin{aligned} &\text{Let } V^\star \leq \sum_{i=1}^{N} \left|\mathfrak{W}_i^b\star\right| \text{ such that } \mathfrak{W}_i^b\star \subseteq \mathfrak{V} \\ &\sum_{v \in \mathfrak{W}_i^b\star} \left(\beta_v * \gamma_{v,i}^\star\right) \geq R_i^b \\ &\text{where } \gamma_{v,i}^\star = \max_v\{\min\{\bigcup_{\forall r \in G_i} \overline{\gamma_{v,r}}\}\} \end{aligned} \tag{13}$$

Now, to achieve a maximum spectral efficiency $\gamma_{v,i}^\star$ for the group G_i as in Eqn. 13 and to limit the search space in the proposed algorithm in Section IV-A2(Alg. 1), we have: $\mathfrak{W}_i^b\star \subseteq \zeta_i \subseteq \mathfrak{V}$, as the *best* PRBs would be available only in *common good* CCs. Omitting the derivation for brevity and page limits, the approximation factor for the worst case is as follows:

$$\left[\frac{V^\star}{V}\right] \geq \log_{\mathbf{Q}+\mathbf{Z}}\left(\mathbf{Q} + \frac{\mathbf{Z}}{\epsilon}\right) \leq 1 \tag{14}$$

where $\mathbf{Q} = 1 + \kappa\left(\ln(N_{sc}) - \ln(\sum_{s=1}^{N_{sc}} e^{-y_s})\right)$ and $\mathbf{Z} = \frac{P}{PL_{\min}.N_0}$, $\epsilon = \frac{PL_{Th}}{PL_{\min}}$, N_{sc} is the number of sub-carriers per PRB, κ is the scaling factor for effective exponential SNR estimation per PRB [15], where $PL_{\min}$ is the minimum path loss reported by any UE. As in Eqn. 14, the closer the value of PL_{Th} towards PL_{min}, the higher is V closer to the optimal solution $V^\star$. It is however bound by the decodeability of the base layer by the UEs of the group.

For any group G_i, it takes $O\left(|\mathfrak{V}|^2\right)$ to determine $\mathfrak{W}_i^b$. So, in total, the set of PRBs for all the groups to allocate the base layer, $\mathfrak{W}^b$, takes $O\left(|\mathfrak{G}|\,|\mathfrak{V}|^2\right)$. Prioritizing the groups takes $O\left(|\mathfrak{G}|^2\right)$. So, the total time complexity is $O\left(|\mathfrak{G}|^2 + |\mathfrak{G}|\,.\,|\mathfrak{V}|^2\right)$.

B. For the Enhancement Layers

Unlike for the base layers, no guarantee is given for serving the enhancement layers; however, when there is substantial room in the aggregated carrier to accommodate the enhancement layers, an optimal CC assignment strategy as formulated in Eqn. 2 from Section III is devised for them.

1) Problem Hardness: The resource allocation for any enhancement layer l, as described in Eqn. 2 of Section III, is equivalent to a variant of the *NP-Complete Multiple Subset Sum* problem [16], stated as follows with representative terms mentioned in braces: Given a set of items (set of PRBs, $\mathfrak{V}$) and N knapsacks (set of groups $\mathfrak{G}$), where each item, $v \in \mathfrak{V}$, has a value $\gamma_{v,i}^{\text{enh}}$ (Here, the profit values and the weight values are the same) with respect to each knapsack i, having a weight requirement $R_i^l = \frac{\mathfrak{R}_i - R_i^b}{L}$, the solution is to determine the subset of items $\mathfrak{W}_i^l$ to be allocated to each knapsack i such that it meets the weight requirements. A solution is *optimal* if the subsets of items assigned to the knapsacks sum up to a *maximum* profit. The subset sum problem is thus reduced to the l^{th} enhancement layer resource allocation problem in polynomial time. In other words, the enhancement layer resource allocation is an *NP-Hard problem*.

Dynamic programming is one of the popular techniques to solve the *Multiple Subset Sum* problem. For a given sub-frame, let $\mathfrak{W}^l$ denote the total PRB set in the aggregated carrier assigned for Enhancement Layer $l \leq L$, where L is the total number of enhancement layers for the subscribed traffic applications. Then, $\mathfrak{W}_i^l$ denotes the PRB set of the CCs assigned to group G_i for layer l, and τ_i^l denotes the Enhancement layer throughput for layer l. Let $\mathfrak{T}(i, \mathfrak{W}^l)$ denote the net enhancement layer throughput obtained by assigning the PRBs of the CCs for the videos subscribed by the groups G_1 to G_i for layer l. There are two comparisons required for every group G_i in the given sub-frame to consider its inclusion in serving the l^{th} enhancement layer, as shown in the Eqn. 15.

$$\mathfrak{T}(i, \mathfrak{W}^l) = \max\left\{\begin{array}{l} \mathfrak{T}(i-1, \mathfrak{W}^l), \\ \max\limits_{\mathfrak{W}_i^l}\{\mathfrak{T}(i-1, \mathfrak{W}^l - \mathfrak{W}_i^l) + \tau_i^l\} \end{array}\right\} \tag{15}$$

However, such dynamic programming solutions are memory and processing-intensive. The optimal solution for each group G_i depends on the optimal solution for the previously-considered group G_{i-1}.So, the full recursion tree has polynomial depth and exponential number of nodes, i.e. $2^N - 1$.The total time complexity is $O(2^N)$. This high time complexity is critical to the performance of the eNB RRM. This paper thus goes on to discuss a greedy approximation algorithm, while also discussing the mechanism to determine the spectral efficiency for each group to provision the enhancement layer.

Algorithm 2 PRB assignment for Enhancement Layer

Begin Proc{*PRB Assignment*}
Set layer counter $l = 1$
Set $\mathfrak{G}_l = \mathfrak{G}$
for every $v \in \mathfrak{V}$ **do**
  if $\mathfrak{G}_l \neq \{\emptyset\}$ **then**
    Set $G_i = \arg\max_{G_i} \left\{ \bigcup_{v \in \mathfrak{V}} \gamma_{v,i}^{\text{enh}} \right\}$ where $G_i \in \mathfrak{G}_l$
    Set $\mathfrak{W}_i^l = \mathfrak{W}_i^l \bigcup \{v\}$
    if $\left(R_{i,l} - \beta_v \gamma_{v,i}^{\text{enh}}\right) < 0$ **then**
      Set $\mathfrak{G}_l = \mathfrak{G}_l - \{G_i\}$
    end if
  else
    if $l < L$ **then**
      Set $l = l + 1$
      Set $\mathfrak{G}_l = \mathfrak{G}$
    end if
  end if
end for
End Proc{*PRB assignment*}

2) PRB Allocation: : Due to a *best-effort* service objective, the spectral efficiency value over any PRB v for any enhancement layer, $\gamma_{v,i}^{enh}$, is chosen such that the aggregated spectral efficiency, which is computed as the spectral efficiency weighed over the number of UEs supporting it (reporting a spectral efficiency value over v that is less than or equal to the chosen one) is maximized, as in Eqn. 16. This step function resolves the tradeoff between the choice of a higher spectral efficiency value, $\gamma_{v,i}^{\text{enh}}$, that enhances the group's enhancement layer throughput and a higher group decodeability.

$$\gamma_{v,i}^{\text{enh}} := \arg\max_{\overline{\gamma_{v,r}}} \{ \bigcup_{r \in G_i} \overline{\gamma_{v,r}} \times U_i^{\overline{\gamma_{v,r}}} \} \tag{16}$$

where $U_i^{\overline{\gamma_{v,r}}}$ is the number of UEs in G_i that support a spectral efficiency value of $\gamma_{v,r}$ on any PRB v. Like base layer assignment, we use a greedy approach that involves sorting of CCs in the aggregated carrier, $\mathfrak{V}$, in increasing order of their central band frequency values. This is followed by determining the *best* group to which each PRB $v \in \mathfrak{V}$ can be assigned. For any PRB v, the *best* group is the one for which its $\gamma_{v,i}^{\text{enh}}$ is the maximum. The algorithm is outlined in Alg. 2.

Assuming L_c as the number of enhancement layers achieved, the net PRB set allocated to G_i, considering the base as well as the enhancement layers, is given by $\mathfrak{W}_i = \mathfrak{W}_i^b \bigcup_{l=1}^{L_c} \mathfrak{W}_i^l$. The CC assignment is done in the first subframe of every downlink frame.

3) Analysis: The mechanism proposed in Alg. 2 suggests that the groups are selected in a non-increasing order of the number of UEs that support higher MCS values per PRB. This would result in achieving larger data rates per PRB and satisfying the bit rate requirements per layer using adequate number of PRBs, satisfying majority of UEs per group, and maximizing the number of enhancement layers. A large number of eMBMS groups could be served simultaneously. Even if it could potentially exhaust the resources of cell-edge UEs and weaker groups, it does not adversely affect throughput as this approach does not use the least-supported MCS levels like the base layer.

Let us prove this by contradiction. Let $\mathfrak{S}_i^{\text{enh}} = \bigcup_{\forall v \in \mathfrak{V}} \gamma_{v,i}^{\text{enh}}$ the set of enhancement layer spectral efficiencies for the group G_i and $\mathfrak{Z}_i^l$ be the PRB set assigned to G_i to provision enhancement layer l. For contradiction, let us assume G_i and G_j be the first pair of out-of-order groups such that for a particular PRB $v \in \mathfrak{V}$, $v = \arg\max_v \{\mathfrak{S}_i^{\text{enh}}\}$ and also, $v = \arg\max_v \{\mathfrak{S}_j^{\text{enh}}\}$ but $\gamma_{v,i}^{\text{enh}} > \gamma_{v,j}^{\text{enh}}$. However, v is assigned to G_j, i.e. $v \in \mathfrak{Z}_j^l$ and $\exists v' \in \mathfrak{V}$, such that $G_i = \arg\max_{G_i} \{\gamma_{v',i}^{\text{enh}}\}$, considering the best-case, and that $v' \in \mathfrak{Z}_i^l$, assigned to G_i. But, there is a higher probability based on the fast-fading random variable, as in Eqn. 9, that $\gamma_{v,i}^{\text{enh}} \geq \gamma_{v',i}^{\text{enh}}$. Referring to Section IV-A2, this is because $f_x \geq f'_x$, the central-band frequencies of the CCs x and x' that contain the PRBs v and v', respectively, as $\mathfrak{V}$ is a sorted aggregated carrier set. So, v' may not provide the *best* MCS levels to G_i, unlike v. So, $\left|\mathfrak{Z}_i^l\right| + \left|\mathfrak{Z}_j^l\right| \geq \left|\mathfrak{W}_i^l\right| + \left|\mathfrak{W}_j^l\right|$ that does not maximize the number of enhancement layers, indexed by l. So, the assumption is false and the proposed algorithm Alg. 2 gives a near-optimal resource allocation for the enhancement layers.

Let $L^\star$ be the *optimal maximum* number of enhancement layers. Let $\mathfrak{W}_i^l\star$ be the PRB set allocated to G_i where $l \in [1, L^\star]$. Then, for each $v \in \mathfrak{W}_i^l\star$, these conditions are met: $G_i = \arg\max_{G_i} \{\gamma_{v,i}^{\text{enh}}\}$ and $v = \arg\max_v \{\mathfrak{S}_i^{\text{enh}}\}$. Alg. 2 considers the former condition and the latter condition depends on the fast fading random variable in Eqn. 9 only, with a lower value resulting in a higher MCS. With the PDF of the random variable as mentioned in Section IV-A2, we have:

$$L^\star - L^c \leq \log_2 \left(\frac{1 + \mathbf{Q}(Y + y)}{1 + \mathbf{Q}Y} \right) \geq 0 \tag{17}$$

where, $E[Y + y] = e^{-Y}(Y + 1) - e^{-(Y + y')}(Y + y' + 1)$, considering limits 0 and y' and $\mathbf{Q}$ is as in Eqn. 14. Here, Y and $Y + y$ are the minimum and maximum values of the fast-fading random variable. We omit the derivation for brevity. L^c is closer to optimality when y takes a smaller value; however, it is bound by the standard deviation of the random variable.

For any PRB $v \in \mathfrak{V}$, the processing time is $O\left(|\mathfrak{G}|^2\right)$. Hence, for any layer l, it takes $O\left(|\mathfrak{V}| \,.\, |\mathfrak{G}|^2\right)$. Therefor, the worst-case time complexity is $O\left(L.\, |\mathfrak{V}| \,.\, |\mathfrak{G}|^2\right)$.

C. Scheduling

The PRBs of a CC, already assigned to a group, are considered for re-assignment to another group only when the latter's traffic requirements are not satisfied using the available set of resources. This results in contention as two or more groups would access the commonly-assigned resources simultaneously. Such claims over the common set of CCs are not accounted in CC assignment. Scheduling tries to resolve this contention by splitting the frequency resources across the contending groups in successive subframes (after the first subframe of a downlink frame). This paper considers a modification to the traditional Proportional Fair Packet Scheduling [17]. The algorithm determines the group to be scheduled on the contending PRBs for the next sub-frame $t \in \mathfrak{T}$ by considering their *required*, *achievable* and *achieved* bit rates, specific to the base and enhancement layers. It computes a Time Domain Scheduling Metric (TDSM) for each group based on the above factors and selects the group with the highest metric value for any PRB to be scheduled on it. The TDSM of a contending group G_i over any common resource v meant for provisioning the base layer during t is computed as follows:

$$TDSM_{i,t}^{b} = \left(\frac{D_{i,v,t}}{Z_{i,v}^{b}} . \left(\frac{R_i^b}{\overline{Z}_{i,v}^{b}} \right) \right) \quad (18)$$

where, $D_{i,v,t}$ is the instantaneous wideband achievable throughput for G_i over the common resource v at subframe t, $Z_{i,v}^{b}$ is its GBR past average throughput over v, $\overline{Z}_{i,v}^{b}$ is the past average throughput over the subframes in the current frame and R_i^b is the AGBR value. The TD metric is higher for the group with a larger AGBR value, a higher achievable throughput, a lower overall past-achieved throughput and a lower past-achieved throughput in the current frame. This emphasizes on achieving a higher degree of *satisfiability* for the system, where *satisfiability* denotes the net fraction of the total subscribed traffic achieved by the groups.

To resolve contention for the resources meant for provisioning enhancement layers, the TD scheduling metric of a contending group G_i over any common resource v during t is computed as:

$$TDSM_{i,t}^{enh} = \left(\frac{D_{i,v,t}}{Z_{i,v}^{e}} . \left(\frac{(\Re_i - R_i^b)}{\overline{Z}_{i,v}^{e}} \right) + S_{i,t}.C'_{i,t} \right) \quad (19)$$

Here, $Z_{i,v}^{e}$ denotes the overall past average achieved Enhancement Layer throughput considering all the layers, $\Re_i - R_i^b$ denotes the aggregate bit rate requirements of all the enhancement layers and similarly $\overline{Z}_{i,v}^{e}$ denotes the past average-achieved Enhancement Layer throughput considering only the current downlink frame. Additionally, as in [17], metrics $S_{i,t}$ denotes the share of the excess capacity for group G_i at time t and $C'_{i,t}$ denotes the excess capacity for group G_i in the aggregated carrier set at subframe t, after base layer provisioning is fulfilled for G_i.

V. Performance Evaluation

This section presents a comprehensive set of results evaluating our proposed mechanisms in both the CC assignment and scheduling phases, focusing on performances of both the base and enhancement layer throughput. The proposed schemes are implemented in the open source LTE/EPC Network simulAtor (LENA) based on the discrete-event Network Simulator NS3 [18]. The salient features of this simulation model include fully-implemented uplink and downlink PHY and MAC functionalities, such as Adaptive Modulation and Coding (AMC), path loss measurements, channel state information feedbacks. These features are extensively used in our simulation for modeling the channel-awareness aspects of our proposed approach. We consider high-end video formats with higher bit rates, involving High-definition video with an MBR of 20 Mbps, real-time HDTV streaming requiring an MBR of 25 Mbps and Blu-ray Disc encoding format requiring an MBR of 40 Mbps, in the above categories to effectively utilize the sophisticated bandwidth and scheduling techniques of LTE-A. We implemented the carrier aggregation module and adaptively set the MCS levels for both the base and enhancement layers for a full-fledged performance evaluation.

TABLE I: NS3 Simulation Parameters

Parameter	**Value**
Cell Size	1 km
Frequency bands	From 800 to 2600 MHz
No. of inter-band CCs	5
Number of PRBs per CC	100 (20 MHz CC)
UE (Node) Mobility Model	Constant (Speed $\approx$ 0)
UE traffic applications	GBR applications
UE distribution in the cell	Uniform
No. of UEs	Maximum 100 (per eNB)
Number of UEs per eMBMS group	Maximum 5
Max. traffic apps per group	5
Loss Model	Jakes Fading Model
Lognormal shadowing	Gaussian (σ=7.5 dBm)
Avg UE T_x power	23 dBm
Avg eNB T_x power	43 dBm
Spectral Efficiency range	0.06 to 5.5
Antenna configuration	1x1
Threshold path loss	-125 dBm
No. of downlink LTE frames (for tests)	5
No. of simulation trials	50

By varying the maximum number of UEs per cell, the proposed CC assignment technique is evaluated against opportunistic channel-aware CC assignment - prioritizing groups with higher channel access probabilities, channel-blind opportunistic traffic-aware CC assignment - prioritizing groups with higher AMBR value, and session-specific MCS assignment [9]. Scheduling techniques are implemented upon our proposed CC assignment to evaluate the proposed scheduling against Blind Equal Throughput (BET) and maximum throughput scheduling techniques [6], [1]. The traffic scenarios considered within the cell for our evaluation purposes include

- *Scenario A*, where traffic contribution is more or less equal from all the UE groups across the cell,
- *Scenario B*, where a larger traffic is contributed by the groups with a higher number of cell-center terminals, and
- *Scenario C*, where a larger traffic is contributed by groups with a higher number of cell-edge terminals.

For presentability, we plot our results only against existing techniques for all the three scenarios in each graph.

Fig. 1 evaluates the achieved base layer GBR throughput as a fraction of the total traffic subscribed by the groups in the system, considering only CC assignment. The improvement as a result of the proposed spectrum-aware CC assignment for the base layer scales to upto 25%, 12% and 15% in terms of the achieved base layer **throughput fractions** (i.e. fraction of the net subscribed traffic achieved as the base layer) for traffic scenarios A,B and C, as we increase the maximum number of UEs per cell from 10 to 100. This is because of an effective assignment of resources high in-demand by

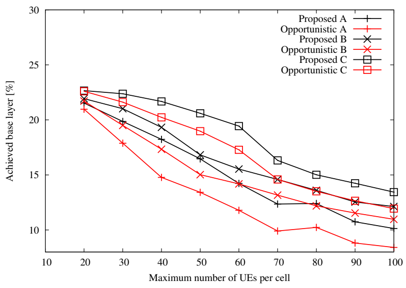

Fig. 1: Percentage of the achieved base layer fraction

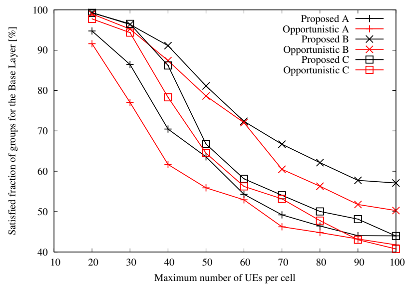

Fig. 2: Fraction of groups satisfied with Base Layer requirements

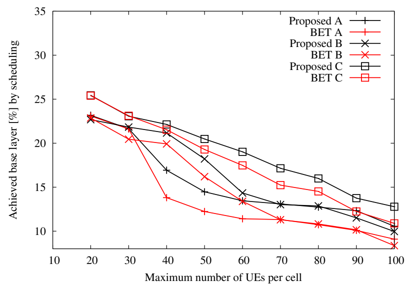

Fig. 3: Percentage of the achieved base layer fraction due to scheduling

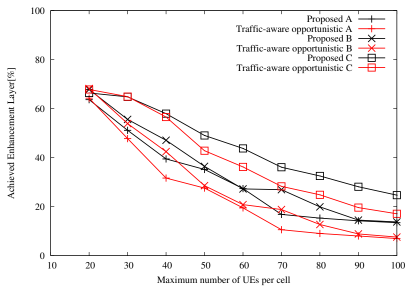

Fig. 4: Percentage of the achieved Enhancement layer fraction

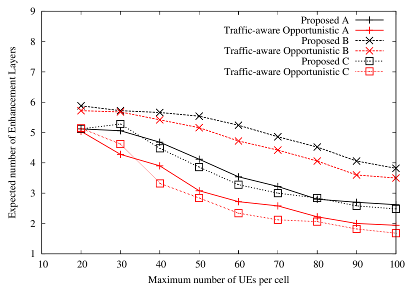

Fig. 5: Achieved average number of enhancement layers

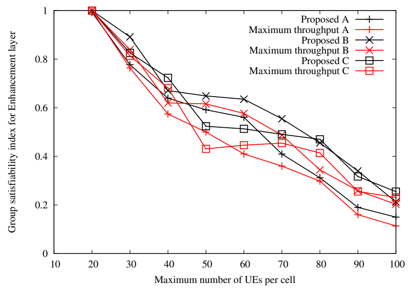

Fig. 6: Group satisfiability index for Enhancement Layer traffic due to scheduling

prioritizing the users with less number of assignable resources, thus preventing them from starvation. This improvement translates to a downlink throughput enhancement of upto 26 Mbps, 15 Mbps and 20 Mbps for the base layer traffic in the three traffic scenarios. Further, Fig. 2 shows the fraction of groups whose base layer traffic requirements are satisfied. With higher guarantees of base layers for each group by a fairer service, the proposed spectrum-aware CC assignment strategy outperforms the opportunistic CC assignment mechanism, as observed. However, the general trend of satisfiability is negative with increase in the maximum number of UEs present in a cell.

Fig. 3 shows the improvement in the achieved base layer throughput as a result of the PFPS-based TDSM discussed in Sec. IV-C. It is evaluated against the BET scheduling algorithm where the metric is simply considered to be the invese of the group's past achieved throughput. However, effective assignment of resources deserves a good degree of channel-awareness aspect in scheduling heuristics, which is provided by the TD scheduling metric devised in this paper. It considers the wideband achievable throughput offered by the PRBs for the group which is estimated by the group's radio channel characteristics and MCS levels and so, a spectrum-aware strategy is more effective in appropriate scheduling and utilization of the resources. Upto 23%, 19% and 22% improvement of the throughput fractions is observed for traffic scenarios A,B and C. This translates to about 30 Mbps improvement in the guaranteed Base Layer throughput.

From Fig. 4, the proposed spectrum-aware *opportunistic* approach for assigning the enhancement layers to the UEs shows a significant improvement over a channel-blind opportunistic traffic-aware CC assignment strategy, where a higher priority is given to UEs with higher AMBR. Leveraging the higher spectral efficiency values for encoding the enhancement layers, an improvement of over 50% in the achieved Enhancement Layer throughput fraction is observed for a maximum of 50 UEs in the cell. This enhancement is three-fold as there is higher congestion in the network with about 100 UEs per cell. As observed in the graph, with a maximum of 100 UEs in the system (worst case), the net enhancement layer throughput is about 13% of the total subscribed traffic by our proposed CC assignment strategy for the scenario A, as against around 7% by the existing traffic-aware opportunistic CC assignment mechanism. B and C traffic scenarios achieve 14% and 25% of the net traffic as enhancement layer throughput, as against 7.6% and 17% as a result of the existing mechanism, respectively. This higher throughput is caused by an increase in the number of enhancement layers as observed in Fig. 5, when compared to the existing technique. In Fig. 6, we evaluate a group's *satisfiability* index for Enhancement Layer traffic. It is defined as the fraction of the satisfied requirements for the enhancement layers for each group, as a result of scheduling. An index of 1 or above for any group indicates that the throughput of the achieved traffic is at least the AMBR of the group. The average *satisfiability* index is computed considering all the groups for their enhancement layer throughput. Upon comparing with *Maximum Throughput* scheduling, the improvement of the throughput fractions by our proposed scheduling heuristic scales upto 37%, 33% and 27% for traffic scenarios A,B and C. This is because the fully opportunistic approach of the *Maximum Throughput* heuristic fails to accommodate all the groups in scheduling.

The super-position of the improvements yielded by the

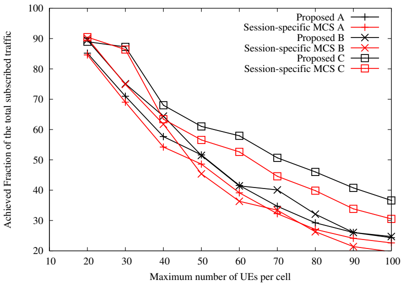

Fig. 7: Achieved fraction of the total subscribed traffic

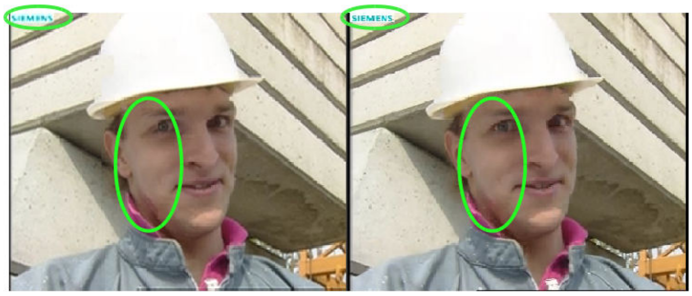

Fig. 8: Effect on the perceptual video quality of the base layer (Left: Opporunistic CA 288x216 - 579 kbps, Right: Proposed CA 352x288 - 703 kbps)

proposed techniques for the base layer and enhancement layers is envisioned in Fig. 7, which evaluates the net achieved fraction of the total subscribed traffic against session-specific MCS assignment [9]. Considering 100 UEs in the system, each with 1x1 T_x/R_x antenna configuration, out of a subscribed traffic of 1.5 Gbps, the proposed CC assignment achieves about 24% of the net subscription, which is equivalent to about 214 Mbps (or approx. 428 Mbps for a 2x2 antenna). The achieved traffic fraction scales to about 85% with 20 UEs in the system, that results in accomplishing 168 Mbps out of a net-subscribed traffic of about 264 Mbps. Fig 8 compares two snapshot frames of the perceptual video quality of the base layers of the Foreman video (which is **one of the many** subscribed traffic applications by the groups), marked with clear distinctions. The frame on the left is due to the opportunistic CC assignment and the one on the right is as a result of our proposed CC assignment, considering a maximum of 90 UEs per cell, 4 traffic applications per eMBMS group (of which, foreman video is one), contributing to uniform traffic distribution. The frame on the left is of resolution 288x216 using a Quantization Parameter (QP) of 20, yielding 579 kbps; whereas our BL frame on the right is 352x288 with a QP of 34, yielding 703 kbps, thereby showing an improvement in the perceptual base layer video quality.

VI. Conclusion

This paper focuses on Carrier Aggregation for provisioning downlink scalable videos to eMBMS groups in a multi-carrier LTE-Advanced system. The main contribution of this paper is devising an spectrum-aware Radio Resource Management mechanism that accommodates the varying channel conditions amongst different members of the same group to schedule the base layer and the enhancement layers with QoS objectives. Accordingly, the modulation and coding schemes are determined for individual layers and the frequency resources are allocated accordingly. Heuristics are proposed to assign and schedule the component carriers for the layers to the groups in terms of physical resource blocks. Extensive performance evaluation is done to assess improvements in base layer, enhancement layer and overall throughputs, and group satisfiability in assignment and scheduling phases. RRM for mobile videos to LTE-A UEs is envisioned for future work.

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