UE-TV: User-centric Energy-efficient HDTV Broadcast over LTE and Wi-Fi

Chetna Singhal *Member, IEEE*, and Swades De, *Senior Member, IEEE*

***Abstract*—This paper presents an innovative multi-faceted architecture, called UE-TV, for user-centric, revenue aware, and energy-efficient TV broadcast. Scalable high-efficiency video coded high definition television (HDTV) content is broadcast over LTE multicast/broadcast single frequency network (MBSFN) along with the available Wi-Fi access points (APs). The proposed framework adaptively encodes the TV content and allocates radio resource based on current network. Stackelberg two-stage game theoretic approach discerns an optimal transmit power at the LTE base stations (eNodeBs) and the proportion of subscribers that are respectively served by eNodeBs and available Wi-Fi APs. Varied user equipment (UE) resolutions, users' energy/price sensitivities, and channel conditions govern the service options and user satisfaction. Our analysis and simulations show that, in comparison with the broadcast schemes over MBSFN without or with adaptive video coding, UE-TV framework significantly enhances the user satisfaction via optimized price/quality trade-off as well as energy saving at the eNodeBs and UEs.**

***Index Terms*—Adaptive multimedia broadcast, HDTV, energy saving, quality-of-user-experience, Long Term Evolution - Advanced, Single Frequency Network**

I. Introduction

Increasing affordability and technological advancements have led to massive growth of multimedia traffic over wireless networks [1]. A multimedia system consists of several heterogeneous components, namely, smart TV, car-infotainment systems [2], laptops, smart phones, netbooks, tablets, and other similar user equipments (UEs) connected over various wireless network technologies (e.g., Wi-Fi, 4G LTE-A cellular). Digital Television (DTV) over wireless networks is one of the key applications that is becoming commonplace, wherein the service providers (SPs) broadcast multimedia content to stationary and mobile users on their heterogeneous devices [3], [4]. Battery life limitation of these devices represents one of the main contributors to user dissatisfaction [5]. Hence, providing ubiquitous multimedia services in an energy-efficient manner is of key interest.

This work was supported by the DST under Grant DST/INSPIRE/04/2015/000793, SERB under Grant SB/S3/EECE/0248/2014, and IIT Kharagpur, ISIRD, under Grant IIT/SRIC/ECE/USW/2016-17.

C. Singhal is with the Dept. of Electronics and Electrical Commun. Engin., IIT Kharagpur, India. S. De is with the Dept. of Electrical Engin. and Bharti School of Telecom., IIT Delhi, India.

While demand for high-definition (HD) multimedia content by DTV subscribers is increasing, wireless networks have limited bandwidth and thus limited data rate support. To reduce the required data rate, a successor of MPEG-4 advanced video coding (AVC)/H.264 standard, called ISO/IEC 23008-2 MPEG-H Part 2 and ITU-T H.265, has been jointly developed by ISO/IEC MPEG and ITU-T VCEG [6], [7]. This technique is also known as High Efficiency Video Coding (HEVC) [8].

Due to energy-intensive nature of multimedia service, a user tends to trade between rate of DTV reception (hence its cost) and UE energy saving. User satisfaction is governed by its sensitivity to service cost and UE energy consumption [9]. Hence, to address the required Quality-of-user-Experience (QoE), it is necessary to factor the individual user's composite interest in UE energy saving and pricing (differential and rate dependent). Recent studies have shown that the UEs consume less energy in Wi-Fi based reception as compared to reception over digital video broadcast (DVB) network and LTE [10], [11]. This fact along with the prevalence of Wi-Fi technology in current-day UEs make it a competitive option for energy and cost efficient DTV service.

Inter-networking and data offloading between cellular and Wi-Fi network is a recent trend followed by operators to support higher data rate [10], [11]. Some advantages of DTV over Wi-Fi along with LTE evolved Multimedia Broadcast Multicast Service (eMBMS) are:

1) On average 90 percent mobile users are active on Wi-Fi [12]. Smartphones already have Wi-Fi feature and can access DTV service on various gadgets over Wi-Fi.

2) DTV over Wi-Fi simultaneously supports multiple devices. This is the need-of-the-hour because often in a household or in an organization people own multiple devices. Hence, instead of having multiple LTE connections and paying for each, DTV over Wi-Fi is a one-stop solution for cost-effective and hassle-free service.

3) A Wi-Fi access point (AP) serving a group of UEs acts as a single LTE client representing these UEs. Thus,

service to the UEs through APs effectively reduces the number of LTE clients from system operation viewpoint, thereby aiding in LTE resource allocation (power, channel rate) and content adaptation (source coding).

A. Related work

For multimedia content delivery, a widely-used standard is H.264/MPEG-4 AVC [13]. Scalable extension of H.264/AVC, called SVC, has been jointly standardized by ITU-T VCEG and ISO/IEC MPEG [14]. HEVC is a next generation standard with up to 50% reduced bit rate compared to the existing standards, while providing an equivalent perceptual quality [15]. Scalable high-efficiency video coding (SHVC) is a scalable extension of HEVC, where the base layer needs to be received by all UEs, while the enhancement layers incrementally improve the QoE. SHVC helps HD content delivery over band-limited wireless channel to the heterogeneous UEs.

Multimedia delivery to mobile UEs is energy-intensive. Energy-aware solutions were proposed in cellular networks [16]. However, these approaches did not consider broadcasting aspects. Energy saving for SVC-based digital video broadcast-handheld (DVB-H) was studied in [17]. Cross-layer aware joint optimization of user experience and energy efficiency for DTV broadcast was proposed in [18]. While time-multiplexed broadcast of scalable DTV programs is of contemporary interest, energy-efficient transmission to heterogeneous users over coexisting wireless networks (LTE and Wi-Fi) is complex [19] and not sufficiently studied in literature yet.

Similar to time-sliced scheduling in DVB-H, time-slotted scheduling over Wi-Fi was studied in [20]. TDMA MAC variants for Wi-Fi were also proposed in [21]. These methods enable efficient multimedia transmission over Wi-Fi, which we intend to exploit in our framework for transmission to heterogeneous UEs.

To improve mobile data services, third generation (3G) mobile unicast data offloading via Wi-Fi is a prevalent solution [22], [23]. A city-wide Wi-Fi offloading architecture proposed in [22] offers improved delivery quality. It was shown in [23], additional UE power saving is possible by delayed offloading and using fast Wi-Fi. Mobile data offloading using Wi-Fi in heterogeneous networks was also discussed in [24]. We extend this offloading feature in our proposed framework for energy-efficient multimedia broadcast over LTE and Wi-Fi.

A Stackelberg game consists of a leader, and a group of followers. The leader chooses its strategy first by anticipating the responses of followers; a follower optimizes its strategy in response to the leader's strategy while competing with the other followers noncooperatively. Stackelberg game has been used before in [25], to study data traffic offloading over the unlicensed spectrum, but not for multimedia broadcast. We have used the Stackelberg game theoretic approach in our proposed energy-efficient HDTV framework over LTE and Wi-Fi.

One way to improve energy efficiency in multimedia multicast is to allocate optimal transmit power to different contents, which was studied using price bidding models [26]. We note that, similar models can be developed for prioritizing the user services with adaptive encoding. Optimal pricing for SVC multicasting to heterogeneous users was investigated in [27]. For network selection in Wireless Local Area Networks, the study in [28] considered categorization of heterogeneous users into four types based on their quality/price sensitivity. As noted in [29], physical layer enhancements are needed for coexistence of DTV transmission over LTE eMBMS. In [30], bargaining based resource allocation was considered for multimedia service discrimination. Equilibrium network pricing policies was used for optimal bandwidth and rate allocation to the budget users [31], [32]. In contrast, in multimedia broadcast context, adaptive SHVC encoding, UE energy saving, price sensitivity for user satisfaction, and SP revenue maximization are of interest in this paper.

Discontinuous reception (DRX) in LTE networks enables UEs to extend battery life [33]. A DRX cycle consists of an 'on duration', when reception over LTE downlink channels is performed, and a 'DRX period', when reception is skipped [34]. In our proposed framework, resource allocation for HDTV broadcast over LTE facilitates DRX to enable UE energy saving.

Temporal variations of DTV traffic and viewing pattern were reported in [35]–[37]. In [38], traffic load during large-scale sporting events were captured to study live dense network scenarios. Motivated by these studies, realistic traffic patterns are considered in our work.

B. eMBMS (physical layer aspects) over LTE-MBSFN

For multicast/broadcast single frequency network (MBSFN) operation, LTE offers provision for adaptively allocating resources for eMBMS and unicast services in mixed mode, where the resources are shared for unicast and eMBMS multi-cell transmission to UEs in the network. In LTE networks, each radio frame (RF) consists of ten sub-frames (SFs) of 1 ms each. Each eMBMS SF consists of 2 slots with 4 to 6 OFDM symbols per slot [39]. Mixed mode eMBMS uses an extended cyclic prefix of 16.2μs length (512 samples) and 15 kHz subcarrier spacing. In frequency division duplex (FDD) transmission, SFs 1,2,3,6,7,8; in time division duplex (TDD), SFs 3,4,7,8,9 are used for MBMS data.

Essential parameters that define the LTE-MBSFN resource allocation are: FDD or TDD transmission mode,

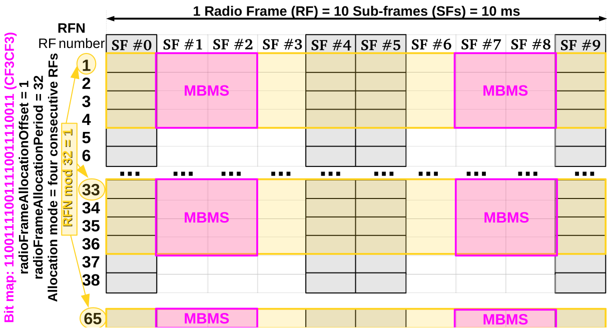

Fig. 1. LTE SF configuration with 5% carrier allocation example for MBSFN operation in FDD mode.

RF allocation offset (to identify the RF number that carries eMBMS data, offset can be between 0 to 7), allocation period (number of RFs after which the pattern of RFs containing eMBMS data repeats, period can be 1, 2, 4, 8, 16, or 32), allocation mode (1 or 4 consecutive RFs that carry eMBMS data), and bitmap (6 or 24 bits, based on allocation mode that define the SFs carrying eMBMS data). At most 192 out of 320 SFs in an allocation period of 32 can be used for eMBMS.

In our framework, we have focused on the downlink of LTE FDD system using licensed spectrum for multimedia broadcast service. Fig. 1 shows an example configuration of the eMBMS SFs in FDD mode with 10 MHz bandwidth, and it uses 5% of carriers for eMBMS. It provides a minimum capacity of 76.150 kbps for channel quality indicator, CQI = 1, and a maximum capacity of 2.777 Mbps for CQI = 15. It has the radio frame allocation offset = 1, radio frame allocation period is 32, and allocation mode is 4 consecutive frames.

Modulation and coding scheme (MCS) is centrally decided by multicast control entity (MCE) of the eNodeBs (eNBs) in MBSFN area. CQI-aware MCS, signal-to-interference-and-noise ratio threshold for 10% block level error rate ($\mathrm{SINR_{th}}$), code rate, and efficiency are listed in Table I for an LTE system [40].

TABLE I
LTE SYSTEM'S OPERATION PARAMETERS

CQI (MCS index)	Modulation $\times 1024$	Code rate (bits/Hz)	Spectral efficiency	$\mathrm{SINR_{th}}$ (dB)
1	QPSK	78	0.1523	9.48
2	QPSK	120	0.2344	6.66
3	QPSK	193	0.3770	4.10
4	QPSK	308	0.6010	1.80
5	QPSK	449	0.8770	0.40
6	QPSK	602	1.1758	2.42
7	16QAM	378	1.4766	4.49
8	16QAM	490	1.9141	6.37
9	16QAM	616	2.4063	8.46
10	64QAM	466	2.7305	10.27
11	64QAM	567	3.3223	12.22
12	64QAM	666	3.9023	14.12
13	64QAM	772	4.5234	15.85
14	64QAM	873	5.1152	17.79
15	64QAM	948	5.5547	19.81

C. Motivation, key features, and contributions

User heterogeneity factors (price and energy sensitivity, UE resolution, content request, and channel condition) need to be considered for system optimization for user-centric multimedia broadcast service solutions.

User-centric cross-layer optimization of HD multimedia broadcast using *LTE and Wi-Fi inter-networking* is the focus of our study. In particular, we propose a user-centric, revenue-aware, energy-efficient HDTV broadcast framework – called *UE-TV*. The novelty of our solution is that, it *jointly accounts for UE heterogeneity, energy and price sensitivities, and service request pattern*, to improve user satisfaction by optimal encoding, transmit power, and modulation schemes. The key features are:

1) UE diversity is accounted in terms of screen resolution: enhanced definition (ED), HD, or full HD (FHD).

2) DTV content is encoded using SHVC optimization, based on the parametric rate and QoE models.

3) Optimum SHVC encoding parameters, LTE resource allocation, and transmission policies are formulated from current traffic pattern.

4) User satisfaction is factored by the user's energy and price sensitivities.

5) It offers differential pricing and provision for HDTV service over coexisting LTE/Wi-Fi technologies.

The main contributions of this paper resulting from the proposed framework are:

1) Optimized multimedia broadcast system is devised to serve heterogeneous users (price/energy sensitive) over wireless network comprising of APs and eNBs.

2) Video encoding parameters and the proposed LTE resource allocation strategy are based on heterogeneous user demand; physical layer MCS is application aware.

3) Formulation of Stackelberg duopoly game for resource sharing enables eNB utility maximization by optimizing LTE eMBMS resource allocation and deciding participation of the set of Wi-Fi APs in HDTV service.

4) Outcome of the game (eNB's transmit power, Wi-Fi AP's participation for providing DTV service, and number of users served by each SP) also enables to improve user satisfaction by appropriately choosing the transmission technologies, namely, LTE or Wi-Fi, based on the users' price, quality, and energy sensitivities, and also depending on the availability of Wi-Fi coverage.

TABLE II

NOTATIONS AND DEFINITIONS USED IN UE-TV FRAMEWORK

Notation	Definition
$R(q,f,s)$	Video rate at q quantization level, f frame rate, and s spatial resolution
$Q(q,f)$	QoE (video quality) at q quantization and f frame rate
$\mathcal{B}$	Set of all SPs
b	SP $b \in \{w,c\}$ is an AP denoted as w, or eNB denoted as c
$\mathcal{W}_b$	Set of APs associated with eNB b
$\mathcal{U}_b^p$	Set of users being served program p by SP b
$u_{i,j}$	user of type j associated with eNB c_i
$\mathcal{L}(t)$	TV load at time t
$\Omega_b(l,p)$	Needed bandwidth for SHVC layer l of program p for SP b
$\pi_b(t), \Pi_b$	subset of resources for TV broadcast, total resources of SP b
$m_l^p(t)$	MCS index for layer l of TV program p
$\phi_b(l,p)$	Fraction of time allocated to transmit layer l of program p by SP b
$\eta_{m(t)}$	Spectral efficiency for MCS index $m(t)$
$\mathcal{P}_b$	Set of TV programs broadcast by SP p
$q_o^p(t)$	Optimal quantization level for program p at time t
$\gamma_b^p(l,t)$	Marginal cost to a user receiving l layers of p from SP b at time t
$\epsilon_b^p(l,t)$	UE energy saving while receiving l layers of p from SP b
V_c	Revenue earned by eNBs
U_b	Number of subscribers (users) served by SP b
μ_b	Utility of eNB b
$\mathbb{P}_{\mathbb{T}}$	Transmit power of eNB
χ_w	Indicator of participation of AP w for DTV broadcast
$\mathcal{X}_b$	Set of indicators for participation of APs associated with eNBb
A_i	User i satisfaction
θ_w	Operational cost of AP
$\theta_c(\mathbb{P}_{\mathbb{T}})$	Operational cost of eNB having a transmit power $\mathbb{P}_{\mathbb{T}}$
n_w	Number of APs in MBSFN coverage area
n_c	Number of cellular LTE eNB in MBSFN coverage area
N	Total number of SPs in MBSFN coverage area

5) The framework additionally allows the UEs to save energy by DRX of time-multiplexed SHVC content over LTE (by sub-frame allocation) or Wi-Fi (by time-slicing).

Compared to adaptive LTE and conventional DTV broadcast, respectively, UE-TV serves 15.36% and 34.58% more UEs with 32.27% and 91.28% higher user satisfaction, while saving 24.81% and 71.29% higher UE energy as well as 21.41% and 36.75% eNB power.

D. Paper organization

Section II describes the system model and proposed architecture. SHVC encoding and LTE resource allocation framework are presented in Section III. Section IV contains the Stackelberg game formulation, UE energy saving model, and user satisfaction model. Section V presents the simulation results. Section VI concludes the paper. Symbols used in the paper are listed in Table II.

II. SYSTEM MODEL

A. Overview of the system

Fig. 2 shows an example scenario. Multimedia streaming over LTE follows eMBMS standard, defined in 3G partnership project (3GPP) release 9, that uses MBSFN. Content provider is the source of HDTV content. Multimedia data is sent to eMB service center (eBM-SC) which is connected to the user and control planes of the eMBMS gateway. The user plane delivers data to eNBs, and the control plane communicates control information to MCE via the mobility management entity (MME). MCE ensures uniform resource block and MCS allocation by all eNBs in a given MBSFN area.

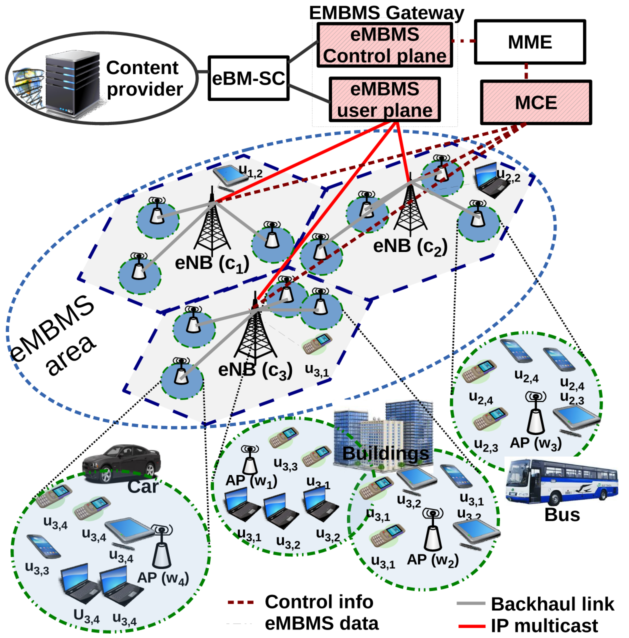

Fig. 2. Example scenario of user-centric multimedia broadcast.

The system model considers an eMBMS area consisting of several eNBs. There are multiple APs within each eNB coverage area. Each of these eNBs and APs are considered as distinct service provider (SP) in the system [41], [42]. An AP receives the content from eNB and broadcasts efficiently to the UEs in its coverage area based on outcome of the Stackelberg game (eNB's transmit power, Wi-Fi AP's participation in DTV service, and number of users served by each SP). The AP is an eNB client which procures the relevant TV programs (all layers) and accordingly pays a price to the eNB. The set of all SPs within the system, $\mathcal{B}$, is defined as:

$$\mathcal{B} = \{b_i | b \in \{w,c\}, 1 \leqslant i \leqslant n_b\}$$
$$b \equiv \begin{cases} c, & \text{if SP is cellular LTE eNB} \\ w, & \text{if SP is Wi-Fi AP} \end{cases} \tag{1}$$

There are N SPs in the system, where $N = n_w + n_c$; w refers to wifi and c to cellular.

Heterogeneous users are sensitive to the price of multimedia service and the battery drainage (energy consumption) of their UE. Hence, in the system, users

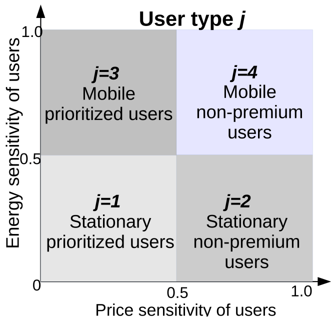

Fig. 3. User types based on energy and price sensitivity.

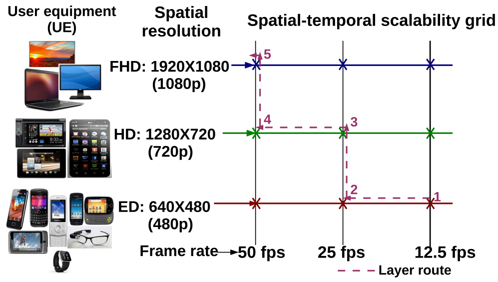

Fig. 4. SHVC spatial and temporal scalable layer grid, and heterogeneous UEs categorized in terms of spatial resolution.

are classified based on their energy and price sensitivity with the following definition for user type.

1) User type: User type j, $j \in \{1, 2, 3, 4\}$, is decided by its price and energy sensitivity. Mapping between user type j and price/energy sensitivity is given as:

$$j=\begin{cases} 1, & \text{if price sensitivity} \leqslant 0.5 \text{ and energy sensitivity} \leqslant 0.5,\\ 2, & \text{if price sensitivity} \leqslant 0.5 \text{ and energy sensitivity} > 0.5,\\ 3, & \text{if price sensitivity} > 0.5 \text{ and energy sensitivity} \leqslant 0.5,\\ 4, & \text{if price sensitivity} > 0.5 \text{ and energy sensitivity} > 0.5.\end{cases}$$

where 0.5 is the threshold of price and energy sensitivity, above which a user is more price/energy sensitive. The chosen sensitivity threshold 0.5 divides the range $[0, 1]$ into equal low and high price/energy sensitivity regions.

Often, mobile users are energy sensitive [43], [44], whereas stationary ones are not – depending on proximity of charging source and UE battery backup. The *non-premium users* are price sensitive [45], while the others that are willing to pay more for better QoE [46] are *premium users*. Premium users are prioritized in the system. Accordingly, stationary prioritized users are type 1, stationary non-premium ones are type 2, mobile prioritized ones are type 3, and mobile non-premium users are type 4. Fig. 3 depicts the four user types.

2) Sample scenario: Each eNB within the eMBMS area may be managed by a different Mobile Network Operator (MNO), and each Wi-Fi AP associated with an eNB may be managed by a different Internet service provider (ISP) [41]. The SPs broadcast the HDTV content (from TV broadcasters and live-TV providers) to heterogeneous UEs. Each user of type j associated with an eNB (i.e. within its coverage area) c_i is denoted as $u_{i,j}$. In Fig. 2, $\mathcal{B} = \{c_1, c_2, c_3, w_1, w_2, w_3, w_4\}$, $n_c = 3$, c_1 to c_3 are the eNBs and w_1 to w_4 are the Wi-Fi APs. w_1, w_2, and w_4 are associated with c_3, whereas w_3 is associated with c_2. A few of the UEs ($u_{2,4}$ and $u_{3,3}$) have smaller screen (ED, lower resolution), some are with medium (HD) resolution ($u_{1,2}$), while the others ($u_{2,2}$) have larger screen (FHD). HDTV content is received by the available APs over a backhaul link [47]. Synchronous broadcast by the eNBs and APs ensures ubiquitous HDTV service flow to the UEs in spite of switching between wireless technologies (Wi-Fi or LTE). For the subset of users being served by an AP, seamless offloading of broadcast service takes place from eNB to the AP. A UE receives a subset of SHVC layers based on its screen resolution, energy and price sensitivity, and channel condition. The users that are unable to receive the DTV content at an acceptable quality over LTE or want to conserve device energy and pay less, opt for Wi-Fi based reception. These sets of users are offloaded from LTE network to Wi-Fi AP for HDTV service.

3) SHVC scalable layers: SHVC encoded content consists of layers; a subset of the received layers decides the QoE level. Fig 4 shows spatial resolution based UE categorization and temporal scalable SHVC layers for each of these UEs. The considered resolution category UEs are FHD (1080p, i.e., 1920×1080 resolution), HD (720p, i.e., 1280×720 resolution), and ED (480p, i.e., 640×480 resolution). Also, three temporal frame rates considered are 50, 25, and 12.5 frames per second (fps).

B. UE-TV system framework

Fig. 5 shows a distributed architecture of UE-TV framework. The *content provider* sends the HDTV content to *eMBMS gateway* that encodes SHVC video at a suitable rate based on the pool of users composition at that instant. *MCE* performs subscriber composition based channel resource and MCS allocation to MBSFN eNBs using SHVC layers and control information from eMBMS gateway. The *eNB* is also the leader of the Stackelberg duopoly game; it performs adaptive power allocation and optimally offloads DTV service to Wi-Fi APs for a subset of users. The *Wi-Fi AP* is the game's follower that performs SHVC local optimization and time-sliced transmission based on the subset of users served by it. One of the SPs, i.e., eNB (leader) or AP (follower) serves the user based on outcome of the game. Each *UE*

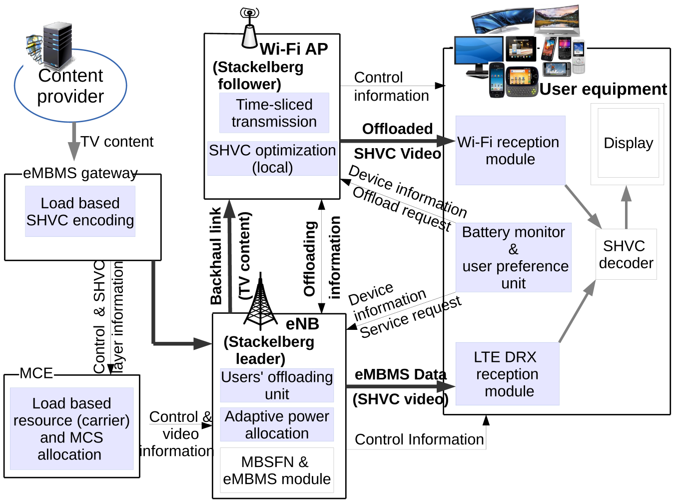

Fig. 5. UE-TV system architecture.

has a battery monitor and the user's energy and price sensitivity dependent preference indicator. Based on the user preference and game's outcome, the DTV content is received by *LTE DRX module* or *Wi-Fi reception module*. The UE displays the decoded DTV content on its screen.

III. Adaptive SHVC Encoding and LTE Resource Allocation in UE-TV

In the proposed framework, load-adaptive resource allocation (resource blocks by eNB, time-slots by Wi-Fi AP, and MCS) is performed for SHVC video broadcast, where parametric rate and QoE models are used. It is necessary to analytically model the video bit rate and quality (QoE) in order to optimize the broadcast service over a wireless network with several eNB, APs, and heterogeneous users. Parametric SHVC rate model helps in defining the data rate requirement for streaming the video, while the QoE model helps in expressing the quality constraint (i.e., acceptable video quality).

A. SHVC rate and quality model

Spatial resolution s, temporal frame rate f, and quantization level q are the coding parameters governing SHVC scalability, layer rates, and QoE. Following the method in [48] for SVC, we derive the parametric rate model for SHVC video. The SHVC video rate encoded with parameters s, f, and q is analytically expressed as:

$$R(q, f, s) = \widehat{R} \cdot \left(\frac{f}{\widehat{f}}\right)^{a} \cdot \left(\frac{q}{\check{q}}\right)^{-æ} \cdot \left(\frac{s}{\widehat{s}}\right)^{d}. \qquad (2)$$

The parameters a, æ, and d are video-specific. $\widehat{R}$ is maximum bit rate of the video with minimum quantization level $\check{q}$, maximum frame rate $\widehat{f}$, and maximum spatial resolution $\widehat{s}$. The resource allocation strategy needs to ensure a transmission rate that is greater than $R(q, f, s)$.

TABLE III
Subjective video quality (QoE) corresponding to parametric video quality measure $Q(q, f)$ and MOS.

MOS	$Q(q, f)$	Quality level
1	0	Bad
2	$(0.0 - 0.25]$	Poor
3	$(0.25 - 0.5]$	Fair
4	$(0.5 - 0.75]$	Good
5	$(0.75 - 1.0]$	Excellent

In this work, QoE of users has been captured by conducting subjective video quality tests in accordance with the methodology recommendations ITU-R BT 500-11 [49] and ITU-T P.910 [50]. Absolute category rating (ACR) method [50] has been used, wherein video test sequences ($\sim$ 10 sec) encoded at different spatial, temporal, and quality levels are presented, spaced by a $\leqslant$ 10 sec assessment time, in a random order. The aim of this subjective video quality study is to ascertain the impact of SHVC video scalability on the QoE. The video quality ratings were recorded on a five-level mean opinion score (MOS) scale (given in Table III) by 25 voluntary subjects in the age group of 20 to 45 years and citizens/residents of countries that cover a diverse geographical region. MOS is a subjective video quality metric or QoE metric that is analytically model in our framework. The quality parametric model in [51] is specified with video-specific parameters λ and g. For a given spatial resolution, $Q(q, f)$ is defined as:

$$Q(q, f) = \widehat{Q} \cdot \frac{1 - e^{(-\lambda \cdot f/\widehat{f})}}{1 - e^{-\lambda}} \cdot \frac{e^{(-g \cdot q/\check{q})}}{e^{-g}}. \qquad (3)$$

$\widehat{Q}$ is the maximum received video quality when coded at quantization $\check{q}$ and frame rate $\widehat{f}$. To normalize, we consider $\widehat{Q}$ to be 100%. We have obtained λ and g of the parametric model $Q(q, f)$ in (3) that approximated the assessment results with root mean square error (RMSE) $< 0.7\%$. $Q(q, f)$ best approximates the subjective quality measure MOS, that indicates the user's QoE. The relationship of $Q(q, f)$ with MOS [51] is given as:

$$\text{MOS} = 4 \times Q(q, f) + 1. \qquad (4)$$

Thus, numerically $Q(q, f)$ corresponds to MOS values and subjective video quality (QoE), given in Table III.

B. Load-adaptive resource allocation

In UE-TV framework, adaptive resource allocation by SPs is based on load. It is conceptually depicted in Fig.

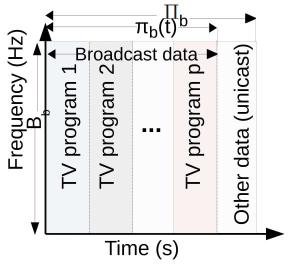

Fig. 6. Load-adaptive resource allocation in UE-TV framework.

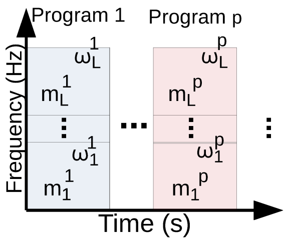

Fig. 7. Resource allocation for SHVC layers by LTE eNB.

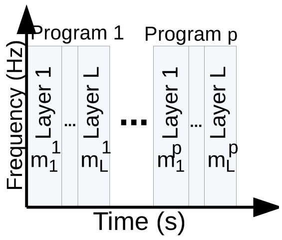

Fig. 8. Resource allocation for SHVC layers by TDMA Wi-Fi AP.

6. Resource allocation for SHVC video layers by eNBs and APs are respectively shown in Fig. 7 and 8. LTE has the provision for adaptively allocating resources for eMBMS and unicast services in mixed mode, where the resources are shared for unicast and eMBMS multi-cell transmission, as shown in Fig. 6. The MCS is centrally selected by MCE for the eNBs in the MBSFN area. The resources for eMBMS transmission are allocated to the SHVC layer of TV programs, as shown in Fig. 7.

Wi-Fi AP broadcasts the scalable HDTV content received from LTE eNB in a layer-aware time-sliced manner (by time-slot based scheduling in TDMA-MAC [20], [21]), as shown in Fig. 8. In TDMA -MAC for Wi-Fi, each frame consists of control, contention, and data time slots [52]. The logical resource allocation by Wi-Fi AP (shown in Fig. 6 and 8) is done by assigning time slots for broadcasting SHVC layers of TV. The MCS is also allocated layer-wise, by the AP, based on CQI. The UEs know a priori the specific layers constituted in the IP packet before receiving the DTV content.

The total usable resource for multimedia broadcast by SP b is Π_b. It denotes the entire set of time slots and subframes per radio frame allocation period (cycle of TV programs) that AP and eNB can use for broadcast, respectively. In UE-TV, a subset $\pi_b(t)$ (out of Π_b) is used for TV broadcast based on the network load.

1) Transmission capacity: Transmission capacity (in Mbps) at time t depends on the allocated resources $\pi_b(t)$ ($0 \leqslant \pi_b(t) \leqslant \Pi_b$), channel bandwidth B MHz, CQI (or MCS index) $m(t)$, and spectral efficiency $\eta_{m(t)}$. CQI and the corresponding spectral efficiency in LTE-A standard are listed in Table I. This capacity is given by:

$$C(B, \pi_b(t), m(t)) = \frac{B \times \pi_b(t) \times \eta_{m(t)}}{\Pi_b}. \qquad (5)$$

2) Bandwidth allocation for layered broadcast of TV programs: Maximum MCS index for a SP b is denoted as M_b; the set of programs being broadcast by the SP b ($b \in \mathcal{B}$) is $\mathcal{P}_b$; bandwidth of SP b is B_b; bandwidth corresponding to SHVC layer l of TV program p ($p \in \mathcal{P}_b$) for SP b is $\Omega_b(l,p)$. It may be noted from Fig. 7 that, the resource allocation by eNB for program p is such that the bandwidth for SHVC content up to layer l is ω_l^p. On the other hand, a Wi-Fi AP allocates the complete bandwidth B_b for each layer l, but allocates different layer-dependent number of slots, as depicted in Fig. 8. Hence, $\Omega_b(l,p)$ can be expressed as:

$$\Omega_b(l,p) = \begin{cases} \omega_l^p - \omega_{l-1}^p, & \text{if } b \text{ is eNB} \\ B_b, & b \text{ is Wi-Fi AP} \end{cases}$$
$$\omega_L^p - \omega_0^p = B_i \text{ if } i \in 1, \cdots, n_c \qquad (6)$$

3) Time allocation for layered broadcast: The time fraction allocated for SHVC layer l of program p by SP b is denoted by $\Phi_b(l,p)$. It can be noted from Fig. 7, at eNB transmission duration of each layer of a program is equal. In contrast, at AP the layers of p have time-multiplexed transmission. Hence, $\Phi_b(l,p)$ is given as:

$$\Phi_b(l,p) = \begin{cases} \frac{\pi_b(t)}{|\mathcal{P}_b|}, & \text{if } b \text{ is eNB} \\ \frac{\pi_b(t)}{|\mathcal{P}_b|} \cdot \left(1 - \sum\limits_{k=1, k \neq l}^{L} \Phi_b(k,p)\right), & \text{if } b \text{ is Wi-Fi AP} \end{cases} \qquad (7)$$

4) Modeling of active users: The active users in each eNB subsystem b ($b \in \mathcal{B}$, b is eNB) are considered to be distributed following homogeneous spatial Poisson process with TV traffic load $\mathcal{L}(t)$ at any given time t of the day as the parameter [53], [54]. As depicted in Fig. 6, over a time-span of Π_b (in terms of radio sub-frames) a subset of resources $\pi_b(t)$ at any given time t is allocated for broadcasting data TV programs and the rest is used for unicast data transmission. $\pi_b(t)$ is a fraction of the maximum, governed by the number of active TV users in each subsystem, and is given as:

$$\pi_b(t) = \sum_{k=1}^{1.2\cdot\hat{\mathcal{L}}} \frac{\mathcal{L}(t)^k e^{-\mathcal{L}(t)}}{(k-1)!} \frac{\Pi_b}{1.2\cdot\hat{\mathcal{L}}} \tag{8}$$

$$\text{such that, } 0 \leqslant \pi_b(t) \leqslant \Pi_b \tag{8a}$$

$$\sum_{\forall p \in \mathcal{P}_b} \sum_{l=1}^{L} C\Big(\Omega_b(l,p), \Phi_b(l,p), m_l^p(t)\Big) \geqslant \sum_{\forall p \in \mathcal{P}_b} \sum_{l=1}^{L} R(q_o^p(t), f_l, s_l) \tag{8b}$$

$$Q(q_o^p(t), f_l) \geqslant 0.25, \forall\, p \in \mathcal{P}_b \text{ and } 1 \leqslant l \leqslant L \tag{8c}$$

$$m_l^p(t) \leqslant m_{\tilde{l}}^p(t), \text{for } l < \tilde{l}, 1 \leqslant l \leqslant L, 1 \leqslant \tilde{l} \leqslant L, \forall p \in \mathcal{P}_b \tag{8d}$$

where $\hat{\mathcal{L}}$ is the maximum TV traffic load in everyday scenario. For example, we consider 20% additional load that might arise during telecast of large-scale events, e.g., Olympics or World Cup [38]. Resource allocation constraint of a SP b, given by (8b), ensures that the network capacity satisfies the data rate requirement ($R(q_o^p(t), f_l, s_l)$, given by (2)) for the SHVC layers. The programs are encoded at an optimal quantization level q_o^p so that the QoE ($Q(q_o^p(t), f_l)$, given by (3)), is acceptable (> 0.25). This constraint is reflected by (8c). Since an SHVC layer $\tilde{l}$ can be decoded only when all layers lower than $\tilde{l}$ are received successfully, MCS for a lower layer l is always less than or equal to that of $\tilde{l}$, given by (8d).

The proposed load-based resource allocation solution is based on Proposition 1 stated below, which gives a unified condition to ensure MCS is allocated to SHVC video layers in accordance with (8), (8a)-(8d).

Proposition 1. *Given that, with MCS $m_l^p(t)$ allocated to SHVC layer l ($1 \leqslant l \leqslant L$) of each TV program p ($p \in \mathcal{P}_b$) for broadcast over SP (LTE and Wi-Fi) b's network and $m_l^p(t) \leqslant m_{\tilde{l}}^p(t)$ for $l < \tilde{l}$, $1 \leqslant l \leqslant L$, and $1 \leqslant \tilde{l} \leqslant L$, we have* $\sum_{l=1}^{L} \eta_{m_l^p(t)} = \Pi_b \cdot |\mathcal{P}_b| \cdot L \cdot \frac{\left(\sum_{l=1}^{L} R(q_o^p(t), f_l, s_l)\right)}{(B_b \cdot \pi_b(t))}$.

Proof: From (5) and (8b), the following should hold true for each program $p \in \mathcal{P}_b$ over an LTE eNB b:

$$\sum_{l=1}^{L} \Omega_b(l,p) \cdot \eta_{m_l^p(t)} \geqslant \frac{\Pi_b}{\pi_b(t)} \cdot |\mathcal{P}_b| \sum_{l=1}^{L} R(q_o^p(t), f_l, s_l). \tag{9}$$

For LTE subsystem, since $m_l^p(t) \leqslant m_{\tilde{l}}^p(t)$ and $\Omega_b(l,p) \geqslant \Omega_b(\tilde{l},p)$, for $l < \tilde{l}$, $1 \leqslant l \leqslant L, 1 \leqslant \tilde{l} \leqslant L$, and $p \in \mathcal{P}_b$, by Chebyshev's sum inequality:

$$\left(\frac{1}{L}\sum_{l=1}^{L} \Omega_b(l,p)\right)\left(\frac{1}{L}\sum_{l=1}^{L} \eta_{m_l^p(t)}\right) \geqslant \frac{1}{L}\sum_{l=1}^{L} (\Omega_b(l,p) \cdot \eta_{m_l^p(t)}). \tag{10}$$

Also, in the UE-TV framework, for LTE subsystem, $\sum_{l=1}^{L} \Omega_b(l,p) = B_b$. Substituting this and (10) in (9),

$$\frac{B_b}{L} \sum_{l=1}^{L} \eta_{m_l^p(t)} \geqslant \frac{\Pi_b}{\pi_b(t)} \cdot |\mathcal{P}_b| \sum_{l=1}^{L} R(q_o^p(t), f_l, s_l). \tag{11}$$

For Wi-Fi subsystem with constraints (8a)−(8d),

$$\sum_{l=1}^{L} (\Phi_b(l,p) \cdot \eta_{m_l^p(t)}) \geqslant \frac{\Pi_b \cdot |\mathcal{P}_b| \sum_{l=1}^{L} R(q_o^p(t), f_l, s_l)}{\pi_b(t) \cdot B_b}. \tag{12}$$

For the Wi-Fi subsystem in UE-TV framework, $\sum_{l=1}^{L} \Phi_b(l,p) = 1$. Moreover, with $\Phi_b(l,p) \geqslant \Phi_b(\tilde{l},p)$, for $l < \tilde{l}$, $1 \leqslant l \leqslant L, 1 \leqslant \tilde{l} \leqslant L, p \in \mathcal{P}_b$. By Chebyshev's sum inequality, substituting in (12) we have:

$$\sum_{l=1}^{L} \eta_{m_l^p(t)} \geqslant \frac{\Pi_b \cdot |\mathcal{P}_b| \cdot L \sum_{l=1}^{L} R(q_o^p(t), f_l, s_l)}{B_b \cdot \pi_b(t)}. \tag{13}$$

With the resource constraints, (11) and (13) give: $\sum_{l=1}^{L} \eta_{m_l^p(t)} = \frac{\Pi_b \cdot |\mathcal{P}_b| \cdot L \cdot \sum_{l=1}^{L} R(q_o^p(t), f_l, s_l)}{\pi_b(t) \cdot B_b}$. Hence proved. □

The proposed load-based resource allocation steps are summarized in Algorithm 1 (based on Proposition 1) that has $\mathrm{O}(|\mathcal{P}_b| \cdot L \cdot \hat{q} \cdot M_b \cdot N)$ complexity. Based on DTV subscriber traffic in each subsystem, it finds the required resources $\pi_b(t)$ for broadcast, optimum quantization level $q_o^p(t)$ for SHVC encoding of program p, and MCS index $\left(m_l^p(t)\right)$ for layer l.

IV. Stackelberg Duopoly and User Satisfaction

We now present the underlying game theoretic formulation that balances revenue (and profit) of the two types of SPs (LTE eNB and Wi-Fi AP) and the number of users getting served by the SPs in the UE-TV system. The framework maximizes the overall user satisfaction that depends on the UE energy saving, price, and user type (defined in Section II-A1). It also minimizes the eNB transmit power while ensuring a minimum acceptable QoE to every served user and giving due consideration to their respective price and energy sensitivities.

A. UE energy saving

UE energy saving depends on the SP (LTE eNB or Wi-Fi AP) from which HDTV service is received. These SPs have different transmission schemes that affect the UE energy consumption by the radio receiver DRX feature. In DRX mode, a UE switches on its radio receiver for receiving the relevant layers (depending on its resolution

Algorithm 1 Load based resource allocation

Input: $\eta_m, B_b, \mathcal{P}_b, \mathcal{L}(t), R(q, f_l, s_l), \forall b \in \mathcal{B}, \forall l \in [1, L], \forall q \in [\check{q}, \hat{q}]$

Pseudocode:

1) **Allocate resources for each SP**
   for each $b \in \mathcal{B}$
   Compute $\pi_b(t)$ using $\mathcal{L}(t)$ in (8)
2) **Allocate MCS and SHVC encoding parameters**
   for each $b \in \mathcal{B}$
   a) **Initialize variables:**
      $m_l^p(t) = 1, \forall\ p \in \mathcal{P}_b, \forall\ l \in [1, L]$
      $\omega_l^p(t) = \frac{B_b}{L}$ and $\Phi_b(l,p) = \pi_b(t)/L$
   b) **Allocation for TV programs broadcast by SP** b
      for each $p \in \mathcal{P}_b$
      Set $flag = 0$
      for each $q = \hat{q}$ to $\check{q}$
        for each $m = 1$ to M_b
          Set $l = L$
          While $flag = 0$ and $l > 0$
            if $\sum_{k=1}^{L} \eta_{m_k^p(t)} \geqslant \Pi_b |\mathcal{P}_b| L \sum_{k=1}^{L} \frac{R(q, f_k, s_k)}{B_b \pi_b(t)}$ then
              Set $flag = 1$
              Set $q_o^p(t) = q$
            else
              Set $m_l^p(t) = m$
              Set $l = l - 1$
            if $flag = 1$ then
              Set $q = \check{q}$
              Set $m = M$

Output: $\pi_b(t)$, $q_o^p(t)$, $m_l^p(t)$, $\forall\ p \in \mathcal{P}_b$, $\forall\ l \in [1, L]$.

and energy/price sensitivity) and saves energy by periodically switching off its radio for the rest of HDTV transmission duration. $|\mathcal{P}_b|$ TV programs, each having L layers, are broadcast by each SP b, $b \in \mathcal{B}$. The UE energy saving model is based on the time-multiplexed scalable video broadcast scheme discussed in [17].

The proposed novel load-based resource allocation for coexisting LTE-A and Wi-Fi networks broadcasts SHVC layers of TV programs in a way that DRX can be used by UEs. This enables the UEs to save energy while receiving broadcast content over either of the two wireless technologies. The quantitative measure of energy saved by UE is later used to define user satisfaction based on the energy and price sensitivity parameters.

HDTV over LTE in UE-TV framework comprises of resource allocation to SHVC layers that are sent by time and frequency multiplexing, as explained in Section III-B and shown in Fig. 7. This enables the UEs to save battery by DRX of the required SHVC layers of the program.

For broadcast by Wi-Fi AP (Fig. 8), each layer corresponds to a different burst within the recurring window. This allows a UE to safely skip the irrelevant bursts.

At time t, $\pi_b(t)$ is the proportion of resources that are allocated (out of maximum Π_b) for DTV broadcast by a SP b. In the proposed scheme, the normalized UE energy saving $\epsilon_b^p(l,t)$ of a user receiving l ($1 \leqslant l \leqslant L$) layers of program p, $p \in \mathcal{P}_b$, is computed as the proportion of time the UE can switch off its radio receiver:

$$\epsilon_b^p(l,t) = \sum_{\substack{x=1 \\ x \neq p}}^{|\mathcal{P}_b|} \sum_{\substack{k=1 \\ k \neq l}}^{L} \Phi_b(k,x) \cdot \frac{\pi_b(t)}{|\mathcal{P}_b| \cdot \Pi_b} - h_b \tag{14}$$

where $b \in \mathcal{B}$, $|\mathcal{B}| = N$, and h_b is the overhead duration that accounts for switching time. Typically h_b is 30 μs for LTE [55] and 200 μs for Wi-Fi [56] network.

B. Revenue/Price bidding models

From the viewpoint of a SP, there would exist certain high priority users in a cell. In order to cater to prioritized broadcast, we consider bidding models that would ensure an increased QoE for the high priority users and at least a fair (MOS $\geqslant$ 3) for the non-premium users. Priority of certain users is in terms of a higher price that they would pay for a higher QoE. Thus, the pricing model should support differential pricing for service to heterogeneous UEs. Extending the logarithmic bidding model that is used for power optimal allocation in [26] to priority users, differential pricing for DTV service is as follows:

$$\Gamma_l^p(t) = \delta_l^p \log_{10}(Q_l^p(q_o^p(t), f_l, s_l) - \check{Q}) + \varrho_l^p. \tag{15}$$

$\Gamma_l^p(t)$ is the cost to a user for receiving l layers ($1 \leqslant l \leqslant L$) of program p ($p \in \mathcal{P}_b$) at time t. $\check{Q}$ is the minimum acceptable quality, $\check{Q} = 0.25, i.e.‘fair’$. $\Gamma_l^p(t)$ is defined according to the logarithmic bidding model for $\check{Q} \leqslant Q(q_o^p(t), f_l) \leqslant 1$, so that $\Gamma_l^p(t) = 0$ for $Q(q_o^p(t), f_l) < \check{Q}$. ϱ_l^p in (15) is the minimum admission price that corresponds to $Q(q_o^p(t), f) = 0.25$, i.e., MOS = 3. δ_l^p is the price control factor (added cost for a higher quality, i.e., with $Q(q_o^p(t), f_l) > 0.25$). Logarithmic model is a concave function of quality, making it practical for use in QoE based differential pricing.

Logarithmic bidding model's utility $\Gamma_l^p(t)$ is a function of parametric video quality ($Q(q_o^p(t), f_l)$, i.e., QoE). It also depends on the specific parameters, i.e., δ_l^p and ϱ_l^p, that are specific to each UE resolution category and users' price sensitivity, i.e., user type (cf. Definition 1).

C. Stackelberg duopoly game formulation for UE-TV

The elements of the duopoly game are as follows:

1) Leaders and followers: Each eNB is the *leader* of the duopoly game, which decides the number of users it serves without the Wi-Fi APs association. Wi-Fi APs are the *followers* of the game and subsequently decides the number of users to serve. Each SP b serves a set of users with program p, $p \in \mathcal{P}_b$, denoted as $\mathcal{U}_b^p$, $b \in \mathcal{B}$.

2) Marginal cost: To a served user receiving l ($1 \leqslant l \leqslant L$) layers, it is different for each SP, defined as:

$$\gamma_b^p(l,t) = \begin{cases} \Gamma_l^p(t), & b \in \mathcal{B},\, b \text{ is eNB} \\ \dfrac{\Gamma_L^p(t) + \frac{\theta_w}{|\mathcal{P}_b|}}{|\mathcal{U}_b^p|}, & b \in \mathcal{B},\, b \text{ is AP.} \end{cases} \tag{16}$$

Cost to a user in eNB b depends on the number of layers l of program p ($p \in \mathcal{P}_b$) received by it and its QoE $Q(q_o^p(t), f_l)$, given by (15). However, marginal cost for HDTV over Wi-Fi AP (above which serving the subset of users from the AP in its coverage area is not cost-effective) depends on the number of users $|\mathcal{U}_b^p|$ that the AP b serves and its operating cost θ_w for DTV broadcast.

3) Output: The game's outcomes at time t are:

i) the eNB's transmit power in order to serve the proportion of subscribers that maximizes its utility;
ii) threshold number of AP subscribers above which a positive utility and a higher QoE is ensured;
iii) the subset of Wi-Fi APs that participate in providing DTV service to the heterogeneous UEs; and
iv) the number of subscribers being served by each SP, i.e., $U_b = \sum_{\forall p \in \mathcal{P}_b} |\mathcal{U}_b^p|$, $b \in \mathcal{B}$.

D. Leader's (eNB's) utility function

Revenue V_c earned from the users is the sum total of marginal costs for DTV over LTE, i.e.,

$$V_c = \sum_{\substack{\forall b \in \mathcal{B} \\ b \text{ is eNB}}} \sum_{i=1}^{U_b} \Gamma_{l(i)}^{p(i)}(t), 1 \leqslant l(i) \leqslant L, p(i) \in \mathcal{P}_b \tag{17}$$

The utility (and profit) of eNB b depends on the number of users it serves, U_b, and the QoE. These are governed by transmit power $\mathbb{P}_\mathbb{T}$. An increased $\mathbb{P}_\mathbb{T}$ helps serve more users with a higher QoE. The associated cost $\theta_c(\mathbb{P}_\mathbb{T})$ (a linear function of $\mathbb{P}_\mathbb{T}$ [57]) also increases with $\mathbb{P}_\mathbb{T}$. A set of APs $\mathcal{W}_b$ are associated with eNB b ($b \in \mathcal{B}$) and each AP pays a price to eNB for receiving all layers of a program. It is defined as: $\mathcal{W}_b \equiv \{\beta |\ \beta$ receives $\mathcal{P}_\beta$ TV programs from eNB b and $b, \beta \in \mathcal{B}\}$. Then, the net utility of eNB b is defined as:

$$\mu_b = \sum_{i=1}^{U_b} \Gamma_{l(i)}^{p(i)}(t) + \sum_{\forall \beta \in \mathcal{W}_b} \sum_{\forall p \in \mathcal{P}_\beta} \Gamma_L^p(t) - \theta_c(\mathbb{P}_\mathbb{T}), b \in \mathcal{B}, b \text{ is eNB.} \tag{18}$$

Proposition 2. *The marginal cost of service by an eNB given by* (16) *and its utility function given by* (18) *are strictly concave functions of transmit power* $\mathbb{P}_\mathbb{T}$ *(*$\breve{\mathbb{P}_\mathbb{T}} < \mathbb{P}_\mathbb{T} < \widehat{\mathbb{P}_\mathbb{T}}$*).* $\breve{\mathbb{P}_\mathbb{T}}$ *is the minimum eNB transmit power required for a non-negative utility (given by* (18)*) and* $\widehat{\mathbb{P}_\mathbb{T}}$ *is its maximum allowable transmit power.*

Proof: The maximum receivable rate R_i by UE i over a channel is related to the transmit power as:

$$R_i = B_b \log_2(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T}). \tag{19}$$

τ_0 is defined as: $\tau_0 = \mathcal{L} N_0 B_b$, where $\mathcal{L}$ is path loss function of the channel, N_0 is noise power spectral density, and B_b is the channel bandwidth of eNB b. τ_0 is a function of link losses and noise, and is user i specific, based on its channel condition. By (2), rate of l layers of program p, encoded with optimal quantization level $q_o^p(t)$ (from Algorithm 1) at time t, is given by:

$$R(q_o^p(t), f_l, s_l) = \tau_1 \cdot \left(\frac{f_l}{\hat{f}}\right)^a \tag{20}$$

$$\text{where} \quad \left(\frac{f_l}{\hat{f}}\right) = \left(\frac{R(q_o^p(t), f_l, s_l)}{\tau_1}\right)^{(1/a)}$$

$$\tau_1 = \hat{R} \cdot \left(\frac{q_o^p(t)}{\check{q}}\right)^{-æ} \cdot \left(\frac{s_l}{\hat{s}}\right)^d.$$

The user i is able to receive SHVC layers up to l layers ($1 \leqslant l \leqslant L$) if $\left\lfloor \frac{R(q_o^p(t), f_l, s_l)}{R_i} \right\rfloor = 1$. The corresponding QoE of user k, derived from (3), (19), and (20), is:

$$\begin{aligned} Q(q_o^p, f_l) =& \tau_2 \cdot \left(1 - e^{-\lambda \cdot f_l/\hat{f}}\right) \\ =& \tau_2 \cdot \left(1 - e^{-\lambda \cdot (R(q_o^p(t), f_l, s_l)/\tau_1)^{1/a}}\right) \\ =& \tau_2 \cdot \left(1 - e^{-\tau_3 \cdot (\log_2(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T}))^{1/a}}\right) \end{aligned} \tag{21}$$

$$\text{where } \tau_2 = \hat{Q} \cdot \frac{e^{(-g \cdot q_o^p(t)/\check{q})}}{e^{-g}}, \ \tau_3 = \lambda \cdot \left(\frac{B_b}{\tau_1}\right)^{1/a}.$$

eNB's utility (by (18)) is a linear combination of marginal service cost to the UEs $\Gamma_{l(i)}^{p(i)}$ ($1 \leqslant i \leqslant U_b$) and the cost associated with $\mathbb{P}_\mathbb{T}$ (linear in $\mathbb{P}_\mathbb{T}$). A non-negative linear combination of strictly concave functions is also strictly concave [58]. Hence, to prove concavity of eNB utility, it is sufficient to prove concavity of $\Gamma_{l(i)}^{p(i)}(t)$ (by (15)). Using (21) and (15), the proof is as follows:

$$\begin{aligned} \Gamma_{l(i)}^{p(i)}(t) =& \delta_{l(i)}^{p(i)} \cdot \log_{10}\left(\tau_4 - \tau_2 \cdot e^{-\tau_3 \cdot (\log_2(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T}))^{(1/a)}}\right) \\ &+ 2 + \varrho_{l(i)}^{p(i)}, \text{ where } \tau_4 = \tau_2 - \check{Q}. \end{aligned} \tag{22}$$

The first and second derivatives of (22) with respect to $\mathbb{P}_\mathbb{T}$ are given in (23) and (24).

$$\begin{aligned} \frac{d\Gamma_{l(i)}^{p(i)}(t)}{d\mathbb{P}_\mathbb{T}} =& \frac{\tau_5 \cdot e^{-\tau_3 \cdot (\log_2(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T}))^{(1/a)}}}{\left(\tau_4 - \tau_2 \cdot e^{-\tau_3 \cdot (\log_2(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T}))^{(1/a)}}\right)} \\ &\cdot \frac{(\log_2(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T}))^{\left(\frac{1}{a} - 1\right)}}{(1 + \tau_0 \cdot \mathbb{P}_\mathbb{T})} \end{aligned} \tag{23}$$

where $\tau_5 = \frac{\delta_l^p \cdot \tau_2 \cdot \tau_3 \cdot \tau_0}{a \cdot \log_e 10 \cdot \log_e 2}$. By definition, the rates

$$\frac{d^2\Gamma^{p(i)}_{l(i)}(t)}{d\mathbb{P}_{\mathbb{T}}{}^2} = \frac{\tau_0 \cdot \tau_5 \cdot e^{-\tau_3 \cdot \left(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})\right)^{(1/a)}}}{\left(\tau_4 - \tau_2 \cdot e^{-\tau_3 \cdot \left(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})\right)^{(1/a)}}\right) \cdot \log_e 2 \cdot (1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})^2} \cdot \left(\frac{-\tau_3 \cdot (\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}}))^{\left(\frac{2}{a}-2\right)}}{a} \right.$$
$$\left. + \left(\frac{1}{a} - 1\right)(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}}))^{\left(\frac{1}{a}-2\right)} - \frac{\tau_2 \cdot \tau \cdot e^{-\tau_3 \cdot \left(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})\right)^{(1/a)}} (\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}}))^{\left(\frac{2}{a}-2\right)}}{a \cdot \left(\tau_4 - \tau_2 \cdot e^{-\tau_3 \cdot \left(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})\right)^{(1/a)}}\right)} - (\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}}))^{\left(\frac{1}{a}-1\right)} \right) \tag{24}$$

given by (19) and (20) as well as QoE given by (21) are positive and real. The values of the third and fourth terms of the linear combination of right hand side of (24) are negative and real. By definition, $\frac{R_i}{\hat{R} \cdot \left(\frac{q^p_O(t)}{\check{q}}\right)^{-æ} \cdot \left(\frac{s_l}{\hat{s}}\right)^d} \geqslant 1$, $\lambda > 1$, and $\frac{1}{a} - \frac{\lambda}{a} - 1 < 0$. Due to this, linear combination of the first two terms on right hand side of (24), i.e., $\frac{\tau_0 \cdot \tau_5 \cdot e^{-\tau_3 \cdot \left(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})\right)^{(1/a)}} (\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}}))^{\left(\frac{1}{a}-2\right)}}{\log_e 2 \cdot \left(\tau_4 - \tau_2 \cdot e^{-\tau_3 \cdot \left(\log_2(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})\right)^{(1/a)}}\right)(1+\tau_0 \cdot \mathbb{P}_{\mathbb{T}})^2} \cdot \left(-\frac{\lambda}{a} \frac{R_i}{\hat{R}\left(\frac{q^p_O(t)}{\check{q}}\right)^{-æ} \cdot \left(\frac{s_l}{\hat{s}}\right)^d)} + \frac{1}{a} - 1\right)$ is also negative and real. Hence, second derivative of marginal service cost $\Gamma^{p(i)}_{l(i)}(t)$ is negative. So, $\Gamma^p_L(t)$ is strictly concave in $\mathbb{P}_{\mathbb{T}}$. This proves strict-concavity of eNB utility μ_b ($b \in \mathcal{B}$, b is eNB) with respect to $\mathbb{P}_{\mathbb{T}}$. □

E. Follower's (Wi-Fi AP's) utility function

Wi-Fi APs associated with the eNBs are the followers in the game, because they decide on the user set to be served after the leader (eNB) has decided. The utility of an AP w ($w \in \mathcal{W}_b$) associated with eNB b ($b \in \mathcal{B}$) is:

$$\mu_w = \sum_{i=1}^{U_w} \Gamma^{p(i)}_{l(i)}(t) - \left(\theta_w + \sum_{\forall p \in \mathcal{P}_w} \Gamma^p_L(t)\right). \tag{25}$$

where, the AP w serves U_w heterogeneous users. θ_w is the constant cost of operating the Wi-Fi AP w, $w \in \mathcal{W}_b$, $b \in \mathcal{B}$, b is eNB for providing DTV service to the UEs in its range. The Wi-Fi AP w receives the L SHVC video layers of $\mathcal{P}_w$ TV programs from eNB b and then transmits these layers to U_w UEs in accordance with resource allocation scheme shown in Fig. 8.

The Wi-Fi AP utility and the number of subscribers in its range decide the AP's participation in DTV service in its range. This is represented by the indicator function χ_w, for Wi-Fi AP w associated with eNB b, ($w \in \mathcal{W}_b$).

$$\chi_w = \begin{cases} 1, & \text{if } \mu_w > 0 \\ 0, & \text{otherwise.} \end{cases} \tag{26}$$

It is evident from (25) and (26) that, there is a minimum threshold number of UEs that need to be in AP w's range to meet its marginal cost for DTV service (i.e., for $\mu_w > 0$). This threshold number of UEs varies with the cost of operation of AP, i.e., θ_w.

F. Served users' satisfaction function

The user i receives the $l(i)$ ($1 \leqslant l(i) \leqslant L$) SHVC video layers (from eNB) of TV program p that have been transmitted at a given time instance t only when the user SINR is less than SINR threshold of $m^p_{l(i)}(t)$. If the user is within the Wi-Fi range, it receives the SHVC video layers from a Wi-Fi AP w ($w \in \mathcal{W}_b$) associated with eNB b if the Wi-Fi AP is participating in providing the HDTV service, i.e., $\mu_w > 0$ and $\mathcal{X}_w = 1$.

The subscriber satisfaction depends on its price/energy sensitivity (defined as user type in Section II-A1), energy saving, and price saving (lower price offered) for the HDTV service received from eNB or Wi-Fi AP.

The user i's satisfaction ($1 \leqslant i \leqslant \sum_{\forall b \in \mathcal{B}} U_b$) in receiving $l(i)$ ($1 \leqslant l(i) \leqslant L$) layers of program $p(i)$ is defined as:

$$A_i = \left\{ \left(\epsilon^{p(i)}_b(l(i), t)\right)^{æ_k} \cdot \left(\gamma^{p(i)}_b(l(i), t)\right)^{\alpha_k} \right\} \tag{27}$$

$æ_k$ ($\leqslant 1$) and α_k ($\leqslant 1$) respectively denote the user's energy and price sensitivity. $æ_k <$ (respectively, $>$) α_k signifies higher energy (respectively, price) sensitivity. $\epsilon^{p(i)}_b$ is obtained from (14); $\gamma^{p(i)}_b$ is obtained from (16).

G. Stackelberg game solution: Nash equilibrium

The Stackelberg duopoly game's equilibrium is obtained from the backward induction method with the extensive-form (with perfect information) representation of the game [59], shown in Fig. 9. A total of n_w APs exist in the MBSFN coverage area, and $\sum_{\substack{\forall b \in \mathcal{B} \\ b \text{ is eNB}}} |\mathcal{W}_b| \leqslant n_w$, Wi-Fi APs participate in the TV broadcast as an outcome of the game. The eNB b (the leader of the game) selects the transmit power $\mathbb{P}_{\mathbb{T}}$ initially and the APs choose to participate or not is given by the set $\mathcal{X}_b = \{\chi_w | w \in \mathcal{W}_b), \sum_{\forall w \in \mathcal{W}_b} \chi_w = \sum_{\substack{\forall b \in \mathcal{B} \\ b \text{ is eNB}}} |\mathcal{W}_b|\}$.

eNB utility μ_b, given by (18), is a strictly-concave continuous function of transmit power $\mathbb{P}_{\mathbb{T}}$. Proposition 2 (in Section IV-D) proves strict concavity of eNB utility.

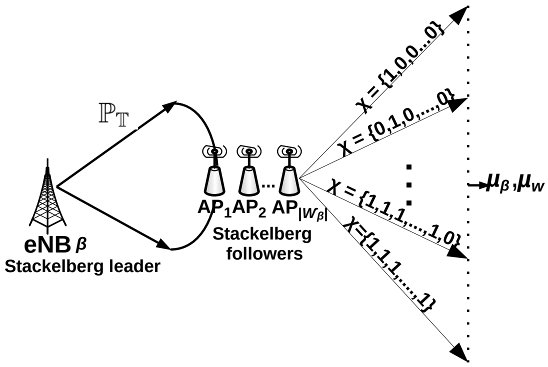

Fig. 9. Extensive-form representation.

Hence, the eNB (leader) utility has a unique maxima with respect to its transmit power. eNB operates at optimal transmit power $\mathbb{P}_{\mathbb{T}}{}^*$, that is also the Nash Equilibrium solution. The utility set for all the APs associated with an eNB b is given as μ_w, $w \in \mathcal{W}_b$. The Wi-Fi APs associated with an eNB individually try to serve the UEs under the condition that the respective utility is non-negative (cf. (26)). Hence, the Wi-Fi APs individually do not deviate from their utility maximization solution in deciding their participation in the DTV service.

$\bigcup_{\forall p \in \mathcal{P}_b} \mathcal{U}_b^p$ are disjoint subsets of subscribers being served by SP $b \in \mathcal{B}$ in the system. eNB transmit power governs $\mathcal{U}_b^p$, $b \in \mathcal{B}$, b is eNB. $\bigcup_{\forall p \in \mathcal{P}_w} \mathcal{U}_w^p$, $w \in \mathcal{B}$, w is AP, is the subset of UEs that are not served by the eNB but are able to get improved service over Wi-Fi. Hence, utility maximization strategy at the eNBs followed by the APs give the Nash Equilibrium solution: eNB transmit power $\mathbb{P}_{\mathbb{T}}{}^*$, indicator function of the APs' χ_w for AP w ($w \in \mathcal{W}_b$) associated with eNB b. These combinedly govern the proportion of users getting served by each SP. The strictly-concave utility function and unique optimal transmit power of eNB proves existence of Nash equilibrium. Stackelberg duopoly iterative algorithm for obtaining the Nash equilibrium solution is presented in Algorithm 2. It has an overall complexity $\mathrm{O}(n_w \cdot |\widehat{\mathcal{P}}| \cdot |\widehat{\mathcal{U}}|)$, where $|\widehat{\mathcal{P}}| = \max_{\forall b \in \mathcal{B}} |\mathcal{P}_b|$ and $|\widehat{\mathcal{U}}| = \max_{\forall b \in \mathcal{B}, \forall p \in \mathcal{P}_b} |\mathcal{U}_b^p|$. To obtain the optimal eNB transmit power $\mathbb{P}_{\mathbb{T}}{}^*$, it is increased by a fraction $\Delta_{\mathbb{P}}$ in each iteration of the algorithm (step 4 of Algorithm 2).

Algorithm 2 Stackelberg duopoly based AP participation and eNB transmit power allocation

Input: $\pi_b(t)$, $q_o^p(t)$, $m_l^p(t)$, $\forall\ p \in \mathcal{P}_b$, $\forall\ l \in [1, L]$, $\mathcal{W}_\beta$, $\forall b, \beta \in \mathcal{B}, \beta$ is eNB.
Pseudocode:
1) **Price for layered TV programs reception**
   for $p = 1$ to P
     for $l = 1$ to L
       Compute $\Gamma_l^p(t)$ using (15)
2) **Set of programs broadcast by SPs to sets of users**
   for each $b \in \mathcal{B}$
     for user i associated with SP b, $\mathcal{P}_b = p(i) \cup \mathcal{P}_b$
     include user i in the set $\mathcal{U}_b^{p(i)}$
3) **UE energy saving for layered TV programs from SPs**
   for each $b \in \mathcal{B}$
     for $p = 1$ to P
       for $l = 1$ to L
         Compute $\epsilon_b^p(l, t)$ using (14)
4) **Wi-Fi AP participation and optimal eNB transmit power**
   for each $\beta \in \mathcal{B}$, β is eNB
     Initialize $flag = 0$, $\mu_\beta = 0$, $\wp = \breve{\mathbb{P}_{\mathbb{T}}}$
     while $\wp \leqslant \widehat{\mathbb{P}_{\mathbb{T}}}$ and $flag = 0$
       for each $w \in \mathcal{W}_\beta$
         for each $p \in \mathcal{P}_\beta$
           for each $i \in \mathcal{U}_\beta^p$
             if i is in coverage area of w then
               Compute user satisfaction A_i for w and β using (27)
               If A_i is higher for w than β then
                 include i in $\mathcal{U}_w^p$
                 include p in $\mathcal{P}_w$
         Compute μ_w using (25)
         if $\mu_w > 0$ then
           $\chi_w = 1$
           $\mathcal{U}_\beta^p = \mathcal{U}_\beta^p \backslash \mathcal{U}_w^p, \forall p \in \mathcal{P}_w$
         else
           $\chi_w = 0$
           $\mathcal{U}_w^p = 0, \forall p \in \mathcal{P}_w$
       Compute $\widetilde{\mu_\beta}$ using (18)
       If $\widetilde{\mu_\beta} > \mu_\beta$ then
         $\mu_\beta = \widetilde{\mu_\beta}$
         $\wp = \wp + \Delta_{\mathbb{P}}$
       else
         $\mathbb{P}_{\mathbb{T}}{}^* = \wp$
         $flag = 1$

Output: $\mathbb{P}_{\mathbb{T}}{}^*$, $\mathcal{U}_b^p$, $\forall\ p \in \mathcal{P}_b$, χ_w, $\forall\ w \in \mathcal{W}_\beta$, $\forall\ b, \beta \in \mathcal{B}, \beta$ is eNB.

V. Overall Performance of UE-TV

For testing the overall performance of UE-TV framework, video content was adaptively encoded using SHVC Test Model 4 (SHM 4) software [60]. SHVC already includes the spatial and temporal scalability in the form of layers (cf. Fig. 4). Suitable encoding parameters: q, LTE SFs allocation, and MCS were obtained from load-based resource allocation (Section III-B). Consequently, the game theoretic model gave eNB transmit power $\mathbb{P}_{\mathbb{T}}$, participation of subset of Wi-Fi APs in broadcast, and the proportion of UEs served by eNBs and Wi-Fi APs.

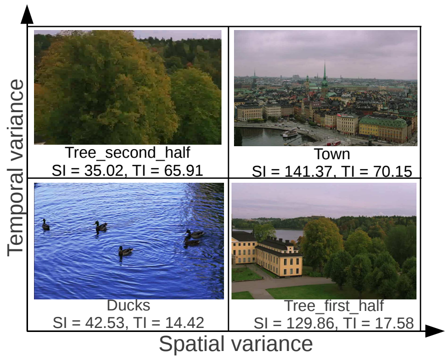

Fig. 10. SI and TI measures of the sample SHVC video sequences.

TABLE IV
SHVC RATE AND QOE MODEL PARAMETERS, AND ACCURACY.

	Para-meter	Town		Tree		Ducks	
		Parameter value	RMSE (%)	Parameter value	RMSE (%)	Parameter value	RMSE (%)
Rate model	a	0.640	0.741	0.739	0.021	0.609	0.667
	æ	2.580	0.030	1.259	0.107	2.957	0.081
	d	0.602	0.578	0.494	0.211	0.631	0.114
QoE model	λ_{ED}	11.442	0.023	10.741	0.003	8.286	0.001
	g_{ED}	0.005	0.032	0.007	0.100	0.004	0.051
	λ_{HD}	17.667	0.108	18.127	0.012	16.047	0.032
	g_{HD}	0.007	0.002	0.006	0.011	0.005	0.025
	λ_{FHD}	15.249	0.019	16.945	0.028	15.149	0.009
	g_{FHD}	0.006	0.071	0.005	0.002	0.008	0.031

A. SHVC video sequences

Three sample HDTV programs: 'Town', 'Tree', 'Ducks', are considered to study the proposed framework. Each of the program's video has different spatio-temporal variance. Spatial resolution and temporal frame rates of these video sequences are as per the spatio-temporal grid shown in Fig. 4. Snapshots of these video sequences along with their spatial/temporal perceptual information (SI/TI) measures are shown in Fig. 10. TI and SI are defined in ITU-T P.910 [50].

SHVC video-specific parameters and accuracy (RMSE) of the parametric rate and QoE models (discussed in Section III-A) are listed in Table IV.

B. Traffic pattern based resource allocation

Fig. 11(d) shows a sample TV traffic pattern over a day (derived from [35]–[37]) and the associated $\pi_b(t)$ proportion of resources allocated for broadcast which is proportional to the subscriber traffic intensity in a subsystem. Correspondingly, Figs. 11(a)-11(c) show the SHVC video layers' adaptive MCS $m(t)$ at various spatial resolutions, frame rates, and q values. It can be seen from Figs. 11(a)-11(c) that a lower q value is suitable only when the broadcast traffic is high. A lower MCS index indicates a lower order scheme, as can be noted from Table I (for LTE-A standard). Since it is a broadcast scheme, a lower MCS index allocated to SHVC layers results in serving more subscribers. Hence, based on the DTV traffic load, the aim of the MCS and $q_o(t)$ allocation algorithm is to select the lowest MCS index (> 1) for the SHVC video encoded at the highest optimum q value such that all video layers get the required resources for broadcast. This is achieved by using the Algorithm 1 based on Proposition 1.

C. eNB and AP performance

Figs. 12(a-d) illustrate the effects of eNB transmit power, in a scenario with 1000 uniformly random distributed heterogeneous UEs. SHVC quantization level, MCS index of the layers, and the number of SFs allocated are determined by traffic load (Section III-B). It is evident that, with increased $\mathbb{P}_{\mathbb{T}}$ more UEs are served (Fig. 12(c)), eNB earns more revenue (cf. (17); Fig. 12(b)), and the served users have higher QoE (Fig. 12(d)). However, with increase in $\mathbb{P}_{\mathbb{T}}$, eNB utility (cf. (18)) increases initially, and decreases subsequently (Fig. 12(a)). This indicates, eNB utility is maximum at $\widecheck{\mathbb{P}_{\mathbb{T}}} < \mathbb{P}_{\mathbb{T}}^* < \widehat{\mathbb{P}_{\mathbb{T}}}$, which is the optimal transmit power at a given traffic load. This is due to marginal increment in number of served users and QoE, as compared to the operation cost at a transmit power higher than $\mathbb{P}_{\mathbb{T}}^*$, resulting in diminished eNB profit. eNB utility maximization gives the optimal transmit power that maximizes eNB profit by balancing between operation cost, and the number of users served, QoE, and revenue.

Fig. 13(a) shows the variation of Wi-Fi AP utility with the increase in number of DTV users in its range. Note that the utility is negative up to a certain number of UEs, and it increases with increased number of UEs. This is because, with a lower number of UEs the Wi-Fi AP operation cost and the price paid for receiving the DTV content from eNB exceeds the revenue earned from the UEs served via APs. Fig. 13(b) shows the variation in threshold number versus normalized operation cost of AP. A higher operation cost results in having a higher threshold number of UEs needed for the AP's participation (i.e., $\chi_w = 1$). Fig. 13(c) shows the AP utility variation with eNB transmit power. The AP is able to receive the relevant TV program layers from eNB only when the normalized eNB transmit power is sufficient. Hence, AP utility is nearly zero for low values of normalized eNB transmit power, which is also evident from Fig. 13(c). The AP utility (given by (25)) increases initially and decreases subsequent to an optimal value.

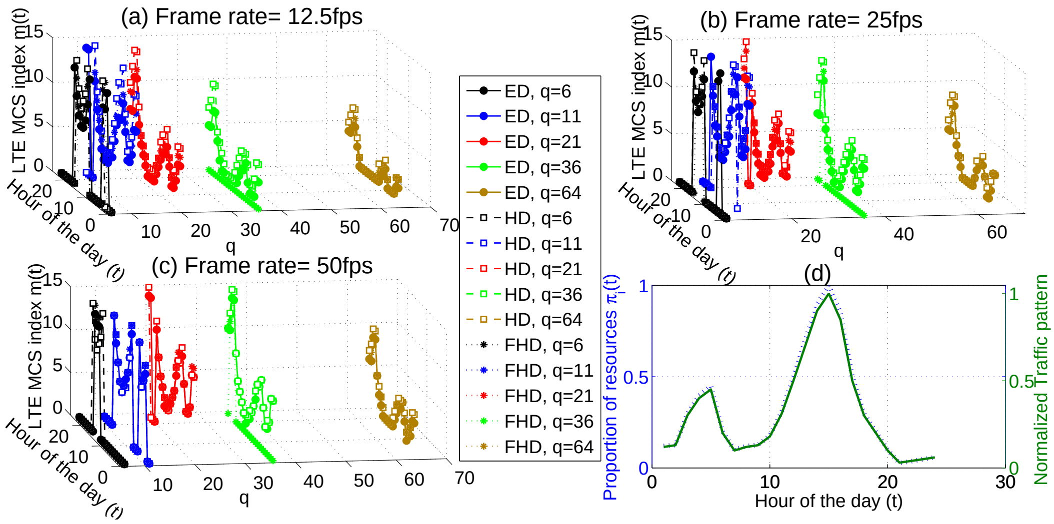

Fig. 11. SHVC video layers transmission MCS index at different traffic pattern over a day, spatial resolutions, q values, and frame rates: (a) 12.5 fps, (b) 25 fps. and (c) 50 fps. (d) The traffic pattern and corresponding proportion of resources, $\pi_b(t)$ allocated for DTV broadcast.

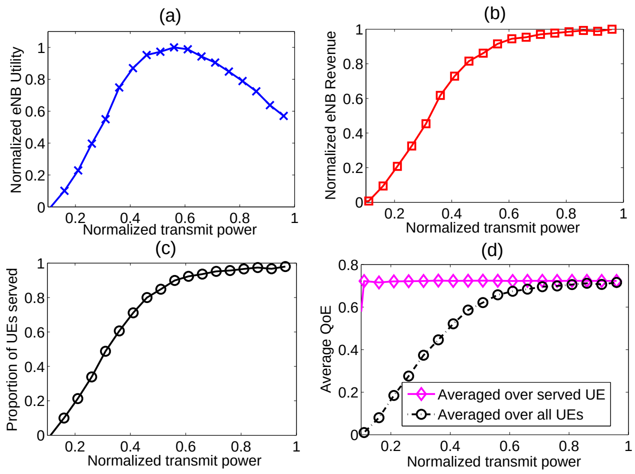

Fig. 12. Effect of eNB transmit power (normalized as $\mathbb{P}_{\mathbb{T}}/\mathbb{P}_{\mathbb{T}\ max}$) on: (a) normalized eNB revenue, (b) normalized eNB utility, (c) proportion of UEs served, and (d) average QoE of the UEs (served/all).

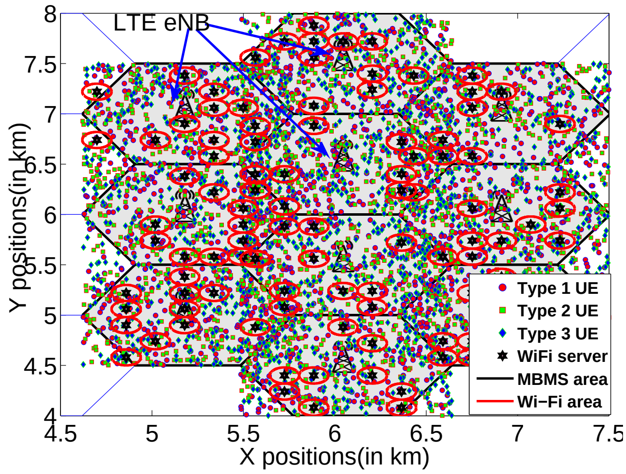

Fig. 14. Simulation scenario with 10 LTE MBSFN eNBs, 25.60% Wi-Fi coverage of the eMBMS area, and 500 randomly distributed HDTV subscribers (having heterogeneous UEs) per eNB.

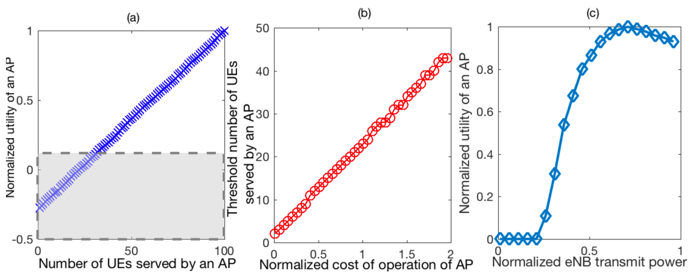

Fig. 13. For 1000 uniformly randomly distributed users and 25% Wi-Fi coverage, (a) Wi-Fi AP utility variation versus number of UEs served by the AP; (b) threshold number of UEs that can be served by AP with respect to the normalized operation cost of the AP; and (c) AP Utility versus the eNB transmit power.

D. Overall simulation scenario and results

A sample simulation scenario is shown in Fig. 14. It comprises of three spatial resolution category of UEs (ED, HD, and FHD) all of which are uniformly randomly distributed. The simulation parameters are listed in Table V. Wireless channel for LTE and Wi-Fi network simulation is modeled with Gaussian fading distribution, log-normal shadowing, and free-space path loss model. [61]–[65]. Equal proportions of each type of user, j ($1 \leqslant j \leqslant 4$) (defined in Section II-A1) and different resolution category (ED, HD, FHD) UEs are present in the system. We have simulated multiple instances ($\geqslant 100$) of network scenarios with random deployment of heterogeneous users within the MBMS area. Three HDTV programs were considered, each carrying one of the video sequences, as described in Section V-A.

Over 24 hours of varying broadcast traffic, Fig. 15(a)

TABLE V
SIMULATION PARAMETERS

Parameter	Value	
	LTE [61]–[63]	Wi-Fi [64], [65]
Channel bandwidth	10 MHz	20 MHz
Frequency	1.8 GHz	2.4 GHz
Carrier spacing	15 KHz	5 MHz
Transmission mode	FDD	N
Number of data carriers	1200	48
Receiver noise figure	7 dB	4.0 dB
Maximum transmitter output power	46 dBm	20 dBm
Transmitter cable and connector loss	2.0 dB	3.0 dB
Transmitter power splitter loss	3.0 dB	3.0 dB
Transmitter antenna gain	18 dBi	10.0 dBi
Receiver antenna gain	0 dBi	-1.89 dBi
Additional losses	14.0 dB (e.g., building)	15.0 dB (e.g., walls)
Receiver noise floor	-97.5 dBm	-96 dBm
Receiver sensitivity	-106.4 dBm	-84 to -68 dBm
Shadowing standard deviation	8 dB	10 dB
Guard interval	16.67μs	0.8 μs

shows the absolute average energy saving of various UE types in the UE-TV framework. The energy saving in ED devices is more than that in HD devices, and it is the least in FHD devices. It is also noted that UE energy saving is more at lower traffic intensities. This is due to SHVC encoding at a higher q value at lower traffic intensities. In contrast, a lower q is used for SHVC encoding (improved QoE) at a higher traffic, which is because more SFs are used for HDTV service over the MBSFN area, resulting in a slightly lower UE energy saving.

Next, UE-TV performance is compared with the '*conventional*' [66] and '*adaptive LTE*' [63], [67], [68] broadcast schemes. *Conventional scheme* simply broadcasts the SHVC HDTV content over LTE MBSFN to the users without adaptive encoding and MCS. In contrast, the proposed *adaptive LTE scheme* broadcasts with optimally encoded SHVC over adaptively assigned LTE MBSFN resources and MCS levels for the SHVC layers.

Served UEs' average energy saving in UE-TV framework with respect to adaptive LTE (24.81%) and conventional (71.29%) schemes (Fig. 15(b)). Fig. 15(c) shows the average eNB power saving with respect to adaptive LTE (21.41%) and conventional (36.75%) schemes.

Figs. 16 and 17 further show the comparative performance of conventional, adaptive LTE, and UE-TV. Fig. 16 shows performances of these schemes with increasing number of users in a system having heterogeneous UEs with 25.60% Wi-Fi coverage. Fig. 16(a) shows that UE-TV results in a higher satisfaction of the served users' (Definition 2, in Section IV-F) with respect to adaptive LTE (32.27%) as well as conventional (91.28%) HDTV.

TABLE VI
UE-TV PERFORMANCE IN DIFFERENT SCENARIOS

Scenario	UE-TV gain with respect to 'Conventional'		UE-TV gain with respect respect to 'Adaptive LTE'	
	User satisfaction	Served user count	User satisfaction	Served user count
Urban	72.91%	52.35%	64.11%	41.29%
Suburban	51.32%	40.76%	43.27%	31.67%
Rural	34.46%	28.19%	28.58%	22.95%

Fig. 16(b) shows that, UE-TV serves more number of subscribers than adaptive LTE (15.36%) and conventional (34.58%) broadcast schemes. UE-TV performance gain is due to inter-networking between eNBs and Wi-Fi APs, which is absent in the other two schemes.

In a scenario with 2000 uniformly randomly distributed heterogeneous users per eNB, Fig. 17 shows the UE-TV performance gain with respect to the two competitive schemes when Wi-Fi coverage in eMBMS area increases. Figs. 17(a) 17(b) show that, user satisfaction as well as the served user count in UE-TV are more with respect to the competitive schemes, which is due to their nonadaptive nature. These performance indexes in UE-TV show an improved trend with increased Wi-Fi coverage. This is because, (i) more Wi-Fi coverage enables better service to more number of users that could otherwise experience poor signal quality from eNB due to shadowing or cell-edge distance; (ii) since a participating Wi-Fi AP, that serves a number of UEs, is treated as one 'client' of the eNB, it has to handle effectively less number of clients, thereby having a better controllability in resource allocation. User satisfaction is also higher due to a lower cost of reception over Wi-Fi.

We have further studied the comparative performance of UE-TV framework in urban, suburban, and rural scenarios, with respect to the two competitive schemes. The eNB coverage range is divided into three zones, zone 1 is closest to eNB, zone 3 is farthest, and zone 2 lies in between zones 1 and 3. The ratio of users in the three zones (i.e., zone 1: zone 2: zone 3) for urban, suburban, and rural areas are 50:25:25, 25:50:25, and 25:25:50, respectively. The Wi-Fi coverage for urban, suburban, and rural areas is considered to be 60-75%, 35-50%, and 15-25%, respectively. The corresponding results in terms of the served user satisfaction gain and served subscriber count gain are noted in Table VI. UE-TV performs better in terms of higher user satisfaction and served user count than the 'Conventional' (on average 52.89% and 40.43%, respectively) and 'Adaptive LTE' (on average 45.32% and 31.97%, respectively) in all the three scenarios.

These results clearly indicate advantages of the UE-TV framework as compared to the conventional (non-

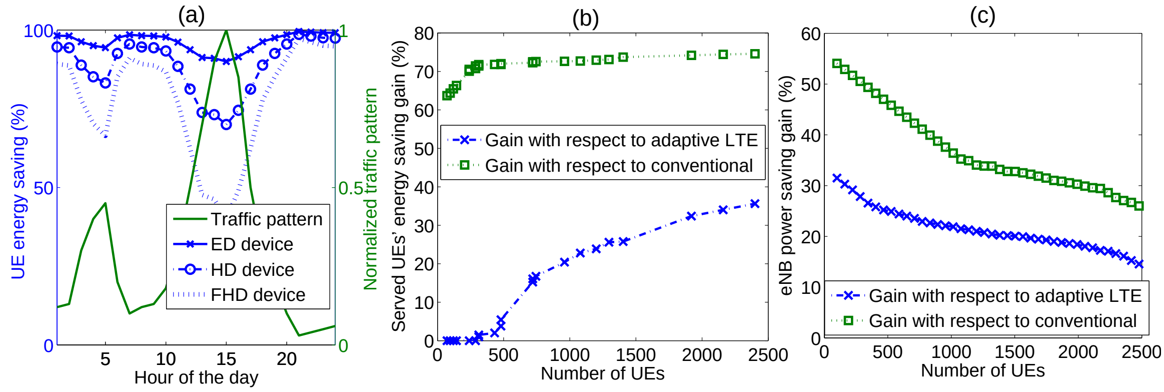

Fig. 15. (a) Absolute average energy saving of served UEs in UE-TV under varying broadcast traffic; (b) Energy saving gain of served UEs with respect to adaptive LTE and conventional DTV; (c) eNB power saving gain with respect to adaptive LTE and conventional DTV.

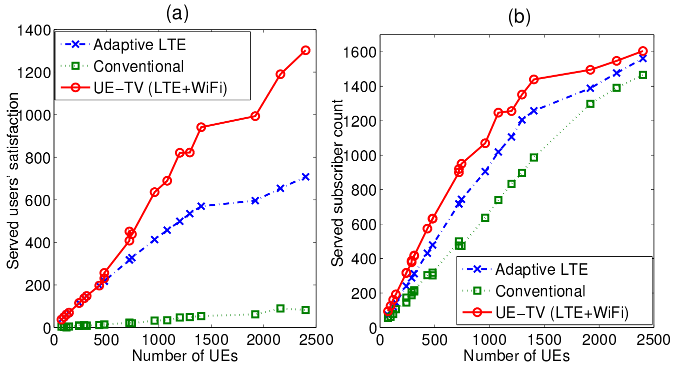

Fig. 16. Served users' satisfaction and served subscriber count versus number of DTV subscribers and 25.60% Wi-Fi coverage.

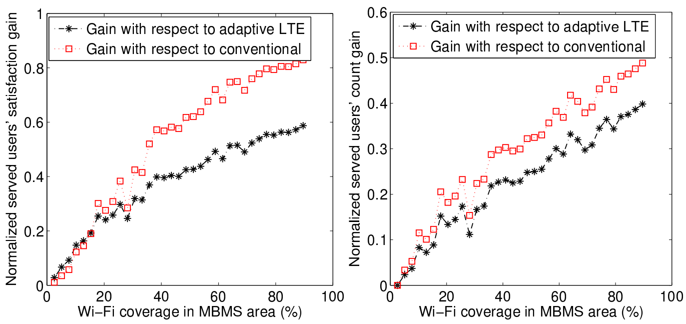

Fig. 17. Gain in served users' satisfaction and subscriber count in UE-TV with respect to adaptive LTE and conventional DTV.

adaptive LTE) and adaptive LTE schemes in terms of more number of users served, better user satisfaction, more energy saving at the UEs as well as the eNBs.

VI. Conclusion

This paper has introduced UE-TV for heterogeneous users with varying display capabilities and price and energy sensitivities. In this framework, heterogeneous traffic load based adaptive resource allocation assigns LTE sub-frames to broadcast adaptively-encoded SHVC video layers of DTV content at suitable MCS levels. Adaptive broadcast over LTE along with the available Wi-Fi ensures service to more number of subscribers at higher satisfaction levels. To aid user satisfaction, Stackelberg game theoretic framework has been used. DTV transmission by time-frequency allocation over LTE and time-slicing over Wi-Fi enables the UEs to save energy by discontinuous reception of relevant video layers. Simulation studies have shown that the coexistent participation of Wi-Fi APs along with the LTE eNBs in the proposed UE-TV framework offers a significantly better performance compared to the conventional broadcast or only LTE based DTV system, in terms of serving more subscribers (34.58% and 15.36%, respectively) with higher levels of satisfaction (91.28% and 32.27%, respectively) and improved UE energy saving (71.29% and 24.81%, respectively) as well as increased eNB power saving (36.75% and 21.41%, respectively).

The proposed UE-TV framework will be extended in our future work to include pricing models that are service provider specific for multimedia broadcast. These could be based on strategies to maximize subscriber base or revenue maximization. Furthermore, the framework will be extended for LTE-A multi-tier architecture.

References

[1] "Cisco visual networking index: Global mobile data traffic forecast update, 2012-2017," *Google Report*, 2013.

[2] Volkswagen of America, Inc, "CES 2015 in detail: Volkswagen introduces advanced gesture control and networking for a new age of mobility," *Media Inform. Rep., CES 2015*. [Online]. Available: http://media.vw.com/doc/1272/

[3] "LTE Broadcast: a revenue enabler in the mobile media era," *Ericsson White Paper*, 2013.

[4] "LTE Broadcast business cases," *Expway White Paper*, 2014.

[5] ChangeWave Research, "New smart phone owners tell us what they really think," 2010.

[6] T. Wiegand, G. J. Sullivan, G. Bjntegaard, and A. Luthra, “Overview of the H.264/AVC video coding standard,” *IEEE Trans. Circuits Syst. Video Technol.*, vol. 13, no. 7, Jul. 2003.

[7] B. Bross, W.-J. Han, J.-R. Ohm, G. J. Sullivan, Y.-K. Wang, and T. Wiegand, “High Efficiency Video Coding (HEVC) text specification draft 10,” JCT-VC of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29/WG 11, Doc. JCTVC-L1003_v9, 2013.

[8] “High Efficiency Video Coding HEVC / H.265,” 2013. [Online]. Available: http://www.vcodex.com/h265.html

[9] “Customers unhappy with subscription television and internet service providers,” *ACSI Telecommun. and Inform. Rep.*, 2014.

[10] C. Singhal, S. De, R. Trestian, and G.M. Muntean, “eWU-TV: User-centric energy-efficient digital TVbroadcast over Wi-Fi networks,” *IEEE Trans. Broadcast.*, vol. 61, pp. 39–55, 2015.

[11] U. Sethakaset, Y. K. Chia, and S. Sun, “Energy efficient WiFi offloading for cellular uplink transmissions,” in *Proc. IEEE Vehicular Technology Conf.*, Seoul, Korea, May 2014, pp. 1–5.

[12] Mobidia, “Understanding today’s smartphone user: Demystifying data usage trends on cellular and Wi-Fi networks,” *Informa telecoms and media: White Paper*, 2012.

[13] G. Iwacz, A. Jajszczyk, and M. Czkowski, *Multimedia Broadcasting and Multicasting in Mobile Networks*. UK: Wiley, 2008.

[14] H. Schwarz, D. Marpe, and T. Wiegand, “Overview of the scalable video coding extension of the H.264/AVC standard,” *IEEE Trans. Circuits Syst. Video Technol.*, vol. 17, no. 9, pp. 1103–1120, Sep. 2007.

[15] G. Sullivan, J. Ohm, W.-J. Han, and T. Wiegand, “Overview of the high efficiency video coding (HEVC) standard,” *IEEE Trans. Circuits Syst. Video Technol.*, vol. 22, no. 12, pp. 1649–1668, Dec. 2012.

[16] R. Trestian, O. Ormond, and G.-M. Muntean, “Energy-quality-cost trade-off in a multimedia-based heterogeneous wireless network environment,” *IEEE Trans. Broadcast.*, vol. 59, no. 2, pp. 340–357, Jun. 2013.

[17] C.-H. Hsu and M. M. Hefeeda, “Flexible broadcasting of scalable video streams to heterogeneous mobile devices,” *IEEE Trans. Mobile Comput.*, vol. 10, no. 3, pp. 406–418, 2011.

[18] C. Singhal, S. De, R. Trestian, and G.-M. Muntean, “Joint optimization of user-experience and energy-Efficiency in wireless multimedia broadcast,” *IEEE Trans. Mobile Comput.*, vol. 13, no. 7, pp. 1522–1535, 2014.

[19] C. Singhal and S. De, “Energy-efficient and QoE-aware TV broadcast in Next-generation heterogeneous networks,” *IEEE Commun. Mag.*, vol. 54, no. 12, pp. 142–150, Dec. 2016.

[20] M. Maity, B. Raman, and M. Vutukuru, “TCP download performance in dense WiFi scenarios,” in *Proc.COMSNETS*, Bangalore, India, Jan. 2015.

[21] I. Hussain, N. Sarma, and D. K. Saikia, “TDMA MAC protocols for WiFi-based long distance networks: A survey,” *Intl. J. Computer Appl.*, vol. 94, no. 19, pp. 1–8, May 2014.

[22] S. Dimatteo, P. Hui, B. Han, and V. Li, “Cellular traffic offloading through WiFi networks,” in *Proc. IEEE MASS*, Valencia, Spain, Oct. 2011, pp. 192–201.

[23] K. Lee, J. Lee, Y. Yi, I. Rhee, and S. Chong, “Mobile data offloading: How much can WiFi deliver?” *IEEE/ACM Trans. Netw.*, vol. 21, no. 2, pp. 536–550, Apr. 2013.

[24] M. Amani, A. Aijaz, N. Uddin, and A. Aghvami, “On mobile data offloading policies in heterogeneous wireless networks,” in *Proc. IEEE VTC Spring*, Dresden, Germany, Jun. 2013.

[25] H. Zhang, Y. Xiao, L. X. Cai, D. Niyato, L. Song, and Z. Han, “A multi-leader multi-follower stackelberg game for resource management in LTE unlicensed,” *IEEE Trans. Wireless Commun.*, vol. 16, no. 1, pp. 348–361, Jan. 2017.

[26] G. C. Sekhar and A. K. Jagannatham, “Optimal power allocation auction for H.264/SVC coded wireless video transmission,” in *Proc. NCC*, New Delhi, India, Feb. 2013, pp. 1–5.

[27] C.-Y. Wang, Y. Chen, H.-Y. Wei, and K. Liu, “Optimal pricing in stochastic scalable video coding multicasting system,” in *Proc. IEEE INFOCOM*, Turin, Italy, Apr. 2013, pp. 540–544.

[28] A. Kumar, R. K. Mallik, and R. Schober, “Duopoly price competition of WLAN service providers in presence of heterogeneous user demand,” in *Proc. IEEE Wireless Commun. Netw. Conf.*, Paris, France, Apr. 2012, pp. 2384–2389.

[29] L. Zhang, Y.Wu, W.Li, K.Salehian, A.Florea, and G.K. Walker, “Improving LTE eMBMS system spectrum efficiency and service quality using channel bonding, non-orthogonal multiplexing and SFN,” in *Proc. IEEE BMSB*, Nara, Japan, 2016.

[30] K.Shin, J.Y.Jung, D.Y.Suh, and S.H.Kang, “Multimedia service discrimination based on fair resource allocation using bargaining solutions,” *ETRI J.*, vol. 34, no. 3, pp. 341–351, 2012.

[31] H. Yaïche, R. R. Mazumdar, and C. Rosenberg, “A game theoretic framework for bandwidth allocation and pricing in broadband networks,” *IEEE/ACM Trans. Netw.*, vol. 8, no. 5, pp. 667–678, Oct. 2000.

[32] R. J. La and V. Anantharam, “Utility-based rate control in the internet for elastic traffic,” *IEEE/ACM Trans. Netw.*, vol. 10, no. 2, pp. 272–286, Apr. 2002.

[33] C. C. Tseng, H. C. Wang, F. C. Kuo, K. C. Ting, H. H. Chen, and G. Y. Chen, “Delay and power consumption in LTE/LTE-A DRX mechanism with mixed short and long cycles,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1721–1734, Mar. 2016.

[34] K. ang, X.Li, H.Ji, and X.Du, “Modeling and optimizing the LTE discontinuous reception mechanism under self-similar traffic,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 7, Jul. 2016.

[35] UMTS and IDATE, “Mobile traffic forecasts 2010-2020 report,” UMTS Forum, London, UK, Tech. Rep. 44, Jan. 2011.

[36] I. Walker, “BBC iplayer monthly performance pack,” BBC Communications, London, UK, Tech. Rep., Oct. 2013.

[37] Ericsson, “TV and media: Identifying the needs of tomorrows video consumers,” Ericsson Consumer Lab, Stockholm, Sweden, Insight Summary Report, Aug. 2013.

[38] N.Browne, S.Perera, and P.Ribeiro, “Harmonic levels and television events,” in *Proc. IEEE PES Gen. Meet.*, Tampa, FL, 2007.

[39] A.Urie, A. Rudrapatna, C.Raman, and J. Hanriot, “Evolved multimedia broadcast multicast service in LTE: An assessment of system performance under realistic radio network engineering conditions,” *Bell Labs Tech. J.*, vol. 18, no. 2, pp. 57–76, 2013.

[40] J. Fan, Q. Yin, G. Li, B. Peng, and X. Zhu, “MCS selection for throughput improvement in downlink LTE systems,” in *Proc. IEEE ICCCN*, Maui, Hawaii, July 2011, pp. 1–5.

[41] Y. Li, F. Baccelli, J. G. Andrews, T. D. Novlan, and J. C. Zhang, “Modeling and analyzing the coexistence of Wi-fi and LTE in unlicensed spectrum,” *IEEE Trans. Wireless Commun.*, vol. 15, no. 9, pp. 6310–6326, Sep. 2016.

[42] W. Huang, L. Ding, D. Meng, J. N. Hwang, Y. Xu, and W. Zhang, “QoE-based resource allocation for heterogeneous multi-radio communication in software-defined vehicle networks,” *IEEE Access*, vol. 6, no. 1, pp. 3387–3399, Jan. 2018.

[43] M.V.J. Heikkinen, J.K. Nurminen, T.Smura, and H.HäMmäInen, “Energy efficiency of mobile handsets: Measuring user attitudes and behavior,” *J. Telemat. Inf.*, vol. 29, no. 4, pp. 387–399, 2012.

[44] S. Deb, K. Nagaraj, and V. Srinivasan, “MOTA: Engineering an operator agnostic mobile service,” in *Proc. Intl. Conf. Mob. Comput. Netw.*, New York, NY, USA, Sep. 2011, pp. 133–144.

[45] M. Krichen, J. Cohen, and D. Barth, “Model for sharing femto access,” in *Proc. Intl. ICST Conf. Perf. Eval. Methodologies and Tools*, Paris, France, May 2011, pp. 254–264.

[46] R. Singh, M. Srinivasan, and C. S. R. Murthy, “A learning based mobile user traffic characterization for efficient resource management in cellular networks,” in *Proc. IEEE CCNC*, Las Vegas, USA, Jan. 2015, pp. 304–309.

[47] Alcatel-Lucent, “Backhaul considerations for LTE and LTE-Advanced - Enhance Quality of Experience and Streamline,” *Application note*, Aug. 2013.
[48] S.Azad, W.Song, and D.Tjondronegoro, “Bit rate modeling of scalable videos using quantization parameter, frame rate and spatial resolution,” in *Proc. IEEE ICASSP*, Dallas, TX, 2010.
[49] *Methodology for the subjective assessment of the quality of television pictures*, ITU-R-BT Recommendation, 500-11, 2009.
[50] *Subjective video quality assessment methods for multimedia applications*, ITU-T Recommendation, P.910, Apr. 2008.
[51] Y. Wang, Z. Ma, and Y.-F. Qu, “Modeling rate and perceptual quality of scalable video as functions of quantization and frame rate and its application in scalable video adaptation,” in *Proc. Intl. Packet Video Wksp.*, Seattle, WA., USA, May 2009.
[52] D. Panigrahi and B. Raman, “TDMA scheduling in long-distance WiFi networks,” in *Proc. IEEE INFOCOM*, Rio de Janeiro, Brazil, Apr. 2009, pp. 2931–2935.
[53] H. Yu, D. Zheng, B. Y. Zhao, and W. Zheng, “Understanding user behavior in large-scale video-on-demand systems,” in *Proc. ACM EuroSys*, Leuven, Belgium, Apr. 2006, pp. 333–344.
[54] W. Trouleau, A. Ashkan, W. Ding, and B. Eriksson, “Just one more: Modeling binge watching behavior,” in *Proc. ACM SIGKDD*, San Francisco, CA, USA, Aug. 2016, pp. 1215–1224.
[55] E.Lähetkangas, K.Pajukoski, G.Berardinelli, F.Tavares, E. Tiirola, I.Harjula, P.Mogensen, and B.Raaf, “On the selection of guard period and cyclic prefix for beyond 4G TDD radio access network,” in *Proc. European Wireless*, Guildford, UK, 2013.
[56] X. Zhang and K. G. Shin, “E-MiLi: Energy-minimizing idle listening in wireless networks,” *IEEE Trans. Mobile Comput.*, vol. 11, no. 9, pp. 1441–1454, Sep. 2012.
[57] N. Faruk, A. Ayeni, M. Muhammad, L. Olawoyin, A. Abdulkarim, J. Agbakoba, and M. Olufemi, “Techniques for minimizing power consumption of base transceiver station in mobile cellular systems,” *Intl. J. Sustainability*, vol. 2, no. 1, pp. 1–11, 2013.
[58] A. Cambini and L. Martein, *Generalized Convexity and Optimization: Theory and Applications*. Springer-Verlag Berlin Heidelberg, 2009.
[59] G. Romp, *Game Theory: Introduction and Applications*. Oxford University Press, 1997.
[60] J. Chen, J. Boyce, Y. Ye, and M. Hannuksela, “SHVC Test Model 4 (SHM 4),” Joint Collaborative Team on Video Coding (JCT-VC) of ITU-T SG 16 WP 3 and ISO/IEC JTC 1/SC 29/WG 11, Geneva, Switzerland, Doc. JCTVC-O1007, 2013.
[61] S. Sesia, I. Toufik, and M. Baker, *LTE UMTS Long Term Evolution, From Theory To Practice*. John Wiley & Sons, 2009.
[62] J. Ikuno, M. Wrulich, and M. Rupp, “System level simulation of LTE networks,” in *Proc. IEEE VTC Spring*, May 2010.
[63] G. Araniti, M. Condoluci, L. Militano, and A. Iera, “Adaptive resource allocation to multicast services in LTE systems,” *IEEE Trans. Broadcast.*, vol. 59, no. 4, pp. 658–664, Dec. 2013.
[64] X. Li and Q.-A. Zeng, “Capture effect in the IEEE 802.11 WLANs with Rayleigh fading, shadowing, and path loss,” in *Proc. IEEE WiMob*, Montreal, Canada, 2006.
[65] E. Perahia and R. Stacey, *Next Generation Wireless LANs: 802.11n and 802.11ac*, 2nd ed. New York, NY, USA: Cambridge University Press, 2013.
[66] D. Lecompte and F. Gabin, “Evolved multimedia broadcast/ multicast service (eMBMS) in LTE-advanced: overview and Rel-11 enhancements,” *IEEE Commun. Mag.*, vol. 50, 2012.
[67] C. Khirallah, D. Vukobratovic, and J. Thompson, “Bandwidth and energy efficiency of video broadcasting services over LTE/LTE-A,” in *Proc. IEEE Wireless Commun. and Networking Conf. (WCNC)*, Shanghai, China, Apr. 2013, pp. 1909–1914.
[68] A. Tassi, C. Khirallah, D. Vukobratovic, F. Chiti, J. Thompson, and R. Fantacci, “Resource allocation strategies for network-coded video broadcasting services over LTE-advanced,” *IEEE Trans. Veh. Technol.*, vol. 64, no. 5, pp. 2186–2192, 2015.

Chetna Singhal (S’13-M’15) received the B.Eng. in Electronics and Telecommunications from the University of Pune, India in 2008, the M.Tech. degree in Computer Technology from the Indian Institute of Technology (IIT) Delhi in 2010, and Ph.D. degree also from the IIT Delhi in 2015. She worked in IBM Software Lab, New Delhi, as a Software Engineer in 2010 for a year. She is currently an Assistant Professor with the Department of Electronics and Electrical Communication Engineering, IIT Kharagpur since 2015. Her research interests are in next generation heterogeneous wireless networks, with emphasis on cross-layer optimization, adaptive multimedia services, energy efficiency, and resource allocation.

Swades De (S’02-M’04-SM’14) received his BTech in radiophysics and electronics from University of Calcutta, India, in 1993, MTech in optoelectronics and optical communication from IIT Delhi, India, in 1998, and PhD in electrical engineering from State University of New York at Buffalo, NY, USA, in 2004.

He is currently a Professor with the Department of Electrical Engineering, IIT Delhi. From 2004 to 2007, he was a tenure-track Assistant Professor with the Department of Electrical and Computer Engineering, New Jersey Institute of Technology, NJ, USA. He was an ERCIM Researcher with ISTI-CNR, Pisa, Italy, in 2004, and has nearly five years industry experience in India on telecom hardware and software development, from 1993 to 1997, and in 1999. His research interests are in communication networks, with emphasis on performance modeling and analysis. Current directions include energy harvesting sensor networks, broadband wireless access and routing, cognitive/white-space access networks, smart grid, and IoT communications.

Dr. De currently serves as a Senior Editor of IEEE COMMUNICATIONS LETTERS, and an Associate Editor of the IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, IEEE WIRELESS COMMUNICATIONS LETTERS, IEEE NETWORKING LETTERS, and IETE Technical Review Journal.