# Energy-Efficient and QoE-Aware TV Broadcast in Next-Generation Heterogeneous Networks

Chetna Singhal and Swades De

***Abstract*—Future networks would comprise of a large number of inter-connected heterogeneous devices that will receive ubiquitous multimedia services over integrated, yet diverse wireless network technologies. In this context, optimization of multimedia broadcast transmissions based on network resources and user-end constraints (price sensitivity, device display, and limited battery) is essential to ensure high Quality-of-user-Experience (QoE). This article discusses underlying challenges, and suggests hybrid system architecture and potential cross-layer adaptive unified solutions for energy-efficient and QoE-aware digital television broadcast services in future heterogeneous network environments. Experimental and architecture-level simulation studies of the cross-layer adaptive strategies demonstrate an increase in user equipment energy saving, QoE, and number of multimedia broadcast/multicast users being served.**

***Index Terms*—Multimedia broadcast/multicast service, digital TV, heterogeneous environments, energy efficiency, quality of experience, cross-layer optimization, network integration.**

## I. INTRODUCTION

5G vision for the future wireless networks is to bring together diverse communication technologies, such as LTE, Wi-Fi, UMTS, and enable the set up, configuration, and maintenance of such heterogeneous network environment in a technology-independent manner. A very wide range of services are expected to be offered in this environment to various human and machine users via diverse device types. The key aspects of focus are pricing policies, energy-efficiency, and Quality-of-user-Experience (QoE). Multimedia-based services and digital television (DTV) in particular are the most popular and the trends indicate an increase in their demands.

It is estimated that the percentage of consumer video traffic over the different types of networks would increase from 60 (at present) to 80 percent by 2018 [1]. Moreover, three-quarters of the video demand would be for high definition (HD) and a quarter for ultra-HD (UHD) video content. Although the average connection speeds and network capacity is increasing with the advent of newer 5G cellular network technologies, the user-demand for popular multimedia content is increasing at an even faster pace [2]. Furthermore, energy-intensive multimedia service access over mobile devices with limited battery capacity affects user satisfaction [1]. Consequently, the overall user experience is still far from optimal. This creates new avenues for network service providers along with DTV broadcasters to provide energy-efficient and QoE-aware ubiquitous multimedia services to heterogeneous customers.

Device-to-device (D2D) communication and multihoming are important features in 5G cellular network technology that improve energy efficiency and system throughput [3], [4]. The latest smartphones have Wi-Fi direct feature for D2D and capability to simultaneously connect to multiple data networks (Wi-Fi and 3G/ LTE) for multihoming. The overall 5G cellular network architecture [5] caters to dense deployment by convergence of network entities and an integrated access network consisting of legacy radio access technologies (RATs), fixed access, and software defined networks. This introduces a paradigm shift in context-aware multimedia services over the next generation wireless communication systems.

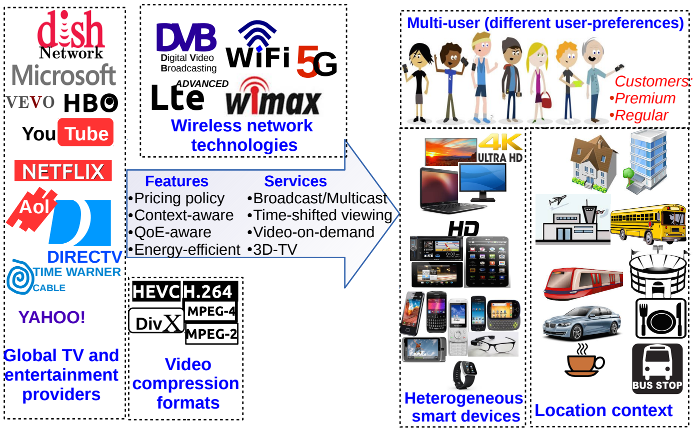

Fig. 1: Heterogeneous multimedia environment.

Multimedia broadcast/multicast transmissions provide simultaneous access to a common service by several types of user equipments (UEs). Fig. 1 shows the elements of a modern day heterogeneous multimedia distribution environment. There are several TV and entertainment providers, such as Netflix, DirectTV, AoL, that offer multimedia content. The content is available in different video compression formats, such as H.264, DivX, HEVC (H.265), that are well-supported by the technologically-advanced smart devices. The broadcast content can be delivered to the premium and regular customers over various wireless network technologies, such as DVB, Wi-Fi, LTE, and 5G. The services are accessed by multiple users that have varied preferences based on location context (such as, in car, bus, train, auditorium, home, office), UE capability, energy (battery capacity), and price sensitivity. The device heterogeneity varies from Ultra-HD screen display

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monitors and smart TVs, as well as portable laptops, tablets, smart phones, to wearable devices like smart watches and Google glass. Presently, entertainment and TV providers support broadcasting, video-on-demand, and time-shifted viewing services. The critical features that these services need to essentially provide are: differential pricing policy, context-awareness, QoE-awareness, and energy efficiency.

This article first discusses the key factors and constraints associated with multimedia broadcast in heterogeneous environments. Subsequently, an adaptive hybrid system architecture and deep cross-layer optimization solution towards energy-efficient and QoE-aware ubiquitous DTV broadcast are proposed. The impact of video scalability on UE energy consumption and QoE in DTV reception over alternative technologies (such as DVB or Wi-Fi) and configurations (router-based, hotspot based, or D2D) are experimentally studied. This constitutes the underlying basis for the energy versus quality trade-off optimization in the proposed framework. Furthermore, support of such solutions in the upcoming technologies are illustrated with use cases. It is noted that, at the system-level the proposed adaptive DTV hybrid framework serves about 30% increased number of customers, results in nearly 60% increased UE energy saving, and improves QoE (mean opinion score, or MOS) by nearly 43% in comparison with the conventional hybrid scheme in the literature. The cross-layer adaptive multimedia broadcast framework discussed in this article is generic and equally applicable to the broadband technologies, such as, LTE, Wi-MAX, 5G, and Wi-Fi, as well as streaming specifications such as MPEG-DASH (which is video-codec agnostic [6]).

## II. ADAPTIVE DTV BROADCAST: KEY FACTORS

Adaptive DTV broadcast employs optimized video encoding and resource allocation in order to provide an energy-efficient and QoE-aware service in a heterogeneous multimedia environment. In this regard, it is essential to study the impact of adaptive/scalable multimedia broadcast on QoE as well as on energy consumption by various elements in the system. It is also essential to employ adaptive DTV pricing to serve the users that are classified based on their willingness to pay.

### *A. Quality of user Experience (QoE)*

QoE is the user-perceived quality of the multimedia service which represents the end-to-end (from media server to the UE playback) system performance [7]. QoE subjectively defines the overall end-user satisfaction. One popular measure of perceived video quality is referred to as MOS, as given in Table I. However the question is, if that is enough to quantify the overall QoE. Since the DTV broadcast content is in the form of video layers, receiving a subset of video layers does not result in loss of pieces of video. Instead, just a lower, yet acceptable, video quality is resulted when the relevant video layers are received by a UE. The latest studies have reviewed the other aspects that affect the user preference. For instance, a statistical survey in [8] suggested that the users prefer a lower-than-excellent yet acceptable video quality on being offered higher UE energy saving. The survey collected user preferences for acceptable video quality levels while being offered a specific amount of energy saving at that quality level. The user preferences for a specific scalable video quality level in order to save UE battery energy are similar in definition to MOS and listed in Table I. The MOS for the scalable video content is obtained using subjective video quality assessment method known as absolute category rating (ACR) that is recommended by ITU-T [7]. In this method the video test sequences (10 sec) [9] are presented one at a time in a random order. These sequences are spaced by a 10 sec assessment time, during which the subject evaluates the quality of the shown sequence on a five-level MOS scale. The subjective video quality assessment was conducted with 40 subjects in the age group of 20 to 50 years and citizens/residents of countries covering a diverse geographical region.

TABLE I: MOS and user preference on video quality in order to save UE battery energy.

| User preference/ MOS score | Quality | Preference level | User preference/ MOS range |
|---|---|---|---|
| 1 | Bad | Not at all preferred | [0,1.5] |
| 2 | Poor | Less preferred | (1.5,2.5] |
| 3 | Fair | Somewhat preferred | (2.5,3.5] |
| 4 | Good | Preferred | (3.5,4.5] |
| 5 | Excellent | Most preferred | (4.5,5] |

### *B. Adaptive DTV pricing*

Scalable video encoding and broadcast depend on certain underlying trade-offs that need to be balanced. This is due to the fact that the same content is transmitted to all the heterogeneous subscribers that have varying channel conditions, price sensitivities, UEs with limited battery energy, and display capability constraints. Feedback (device capability, content request, preferences, and channel condition) from the UEs help the service provider to adaptively encode and transmit the multimedia content in accordance with the subscribers' needs.

In addition to the energy and quality factors, users sensitivity towards price (DTV service charges) also needs to be accounted in the QoE optimization solutions. In order to serve the *premium* as well as price sensitive (i.e. *regular*) customers, differential pricing scheme needs to govern the DTV service revenue policy. Considering such a logarithmic pricing model [9] for differential DTV service, the price for a customer $k$ receiving the DTV content at scalability level $s$, can be defined as:

$$\mathcal{P}_k(s) = a_{s,k}\log_{10}(\text{MOS} - \text{MOS}_{min}) + b_{s,k} \qquad (1)$$

Where, $a_{s,k}$ is the price control factor (ensures an increased price for higher video quality) and $b_{s,k}$ is the minimum admission price. $a_{s,k}$ and $b_{s,k}$ depend upon the type of customer ("premium" or "regular") and the multimedia scalability level $s$. For a "premium" customer, $k_1$ and "regular" customer $k_2$, $a_{s,k_1} > a_{s,k_2}$. This model ensures that the DTV service price is applicable only for the video quality delivered above a certain MOS$_{min}$, which is the minimum acceptable value of MOS corresponding to "Fair" video quality, i.e. 2.5 (given in Table I).

### C. UE energy consumption

A multimedia broadcast system involves energy consumption at the transmitters (wireless base station (BS) or access point (AP)) and the UEs. Energy-intensive task at the transmitter is to broadcast the content, whereas at the UE it is due to reception, processing (decoding and playback), and display. The factors governing the UE energy consumption are transmission technology and video scalability. Video scalability is in terms of spatial resolution, temporal frame rate, and quantization parameter (QP, where $1 \leq QP \leq 51$, [10]).

To study the impact of broadcast reception at various video scalability levels and also to study the effect of wireless access technology on the UE battery energy consumption, we have conducted the UE battery discharge measurements using an Arduino (Duemilanove and Uno) open-source electronics platform based setup, shown in Fig. 2. The UE battery was connected in series with a low-value resistor (0.18 Ohm, tolerance: 5 %) to a Java based setup (on a laptop) that continually records the instantaneous battery power consumption values $Power_k$ (at time= $k$ sec), over a duration of $T$ seconds ($1 \leq k \leq T$). The test video sequences [9] are of 10 seconds duration each, i.e. $T = 10$. The mobile devices used in the experiments were Vodafone Smart Mini, Samsung Galaxy devices (Grand, Y Duos, Tab 3.8.0, Tab S 10.5), Sony Ericsson Xperia Arc, Viliv tablet. The DTV content from RTÉ (Raidió Teilifs Éireann) network in Ireland was received over digital video broadcast (DVB) wireless technology. The scalable DTV content was also received over Wi-Fi (configurations: D2D, hotspot, and router) to study the impact of wireless technology on UE energy consumption. The energy efficiency per UE served in the DTV broadcast framework is obtained experimentally and is given as follows:

$$\text{UE battery energy discharge [J]} = \sum_{k=1}^{T} Power_k \text{ [W]}. \qquad (2)$$

The experimental readings were averaged over ten iterations, conducted in the same conditions to average out the devices' intrinsic and environmental uncertainties. Initially the devices were fully charged and initial observation corresponding to a blank video sequence of 5 seconds was discarded. The results are presented in Section IV, where we discuss the impact of transmission technology and video scalability.

### D. 5G and beyond system architectures for multimedia service

In terms of energy-efficient and QoE-aware multimedia broadcast services over next generation networks (NGN), the overall system architecture needs to incorporate the multiple RATs, D2D, and multihoming subsystems. This in turn would involve centralized and distributed operation of network entities. Intelligently optimizing the network resource usage would benefit the service providers' goal of profitable functioning (power saving, earning more revenue, increased subscriber base), while the subscribers gain by experiencing improved QoE at a lower price and with more energy efficiency.

Table II presents the key aspects of centralized and distributed system architectures for QoE-aware multimedia service in unified NGN. It gives a brief overview of the solutions in the literature with the specified underlying framework that can be extended for network integration and services in 5G and beyond cellular networks. It also lists the associated advantages, disadvantages, and additional essential factors of the corresponding architecture and its solutions. It can be observed from the table that, in a centralized framework, broker is the primary entity that centrally controls adaptive resource allocation and pricing policy as well as provides adaptive multimedia broadcast over multi-RAT network. In contrast, in a distributed framework, each network entity (AP, BS) individually allocates network resource and adaptively controls the pricing policy in a decentralized manner. In heterogeneous networks, RAT selection can be based on a network-centric (centralized), user-centric (distributed), and game-theoretic [11] or conjoined [12] (hybrid) framework. A decentralized network level control and centralized component level control can ensure flexibility, scalability, and efficient utilization of network resources [12].

## III. CROSS-LAYER ADAPTIVE DTV BROADCAST IN NGN

This section discusses the proposed cross-layer adaptive multimedia broadcast system and adaptive hybrid architecture for energy-efficient and QoE-aware DTV broadcast over a heterogeneous multimedia environment in NGN.

### A. Cross-layer adaptive DTV broadcast system

Fig. 3 shows an energy-efficient, QoE-aware, deep cross-layer adaptive solution for DTV broadcast service to the heterogeneous UEs. The multimedia server stores, processes, and encodes the multimedia content. It then sends this content to the service provider's transmitter. The coverage area and received SNR increases with increase in BS transmission power, which in turn serves an increased number of users. However, the revenue gain is not necessarily to the same extent each time there is an increment in transmission power. Hence, to maximize its revenue, the service provider allocates appropriate transmission power to the BS to ensure QoE of an optimal set of end-users [9]. The transmitter then transmits the scalable video layers over the chosen wireless interfaces in blocks (time-slicing in DVB-H, TDMA in Wi-Fi, and time-frequency resource blocks in LTE).

Fig. 3(a) depicts the time-sliced DVB transmission of scalable video layers. Broadcast transmission of scalable video layer contents in blocks allows the heterogeneous UEs to receive a sub-set of layers based on their display capability, energy constraint, or price sensitivity. User information is conveyed to the server and service provider (transmitter). The UE radio receivers are switched-on only for the reception of relevant video layers, and switched-off during the rest of the transmission burst. This allows the heterogeneous UEs to save their respective battery energy while receiving the adaptive DTV broadcast content.

Scalable video layers 1 through 7 are in accordance with the route in spatial resolution - temporal frame rate grid of Fig. 3(a). The different number of layers correspond to: HD 720p (1280×720), D1 (720×240), and CIF (common interchange format, 352×288) spatial resolution categories. The temporal frame rates considered are: 3.75, 7.5, 15, 30, and 60 fps.

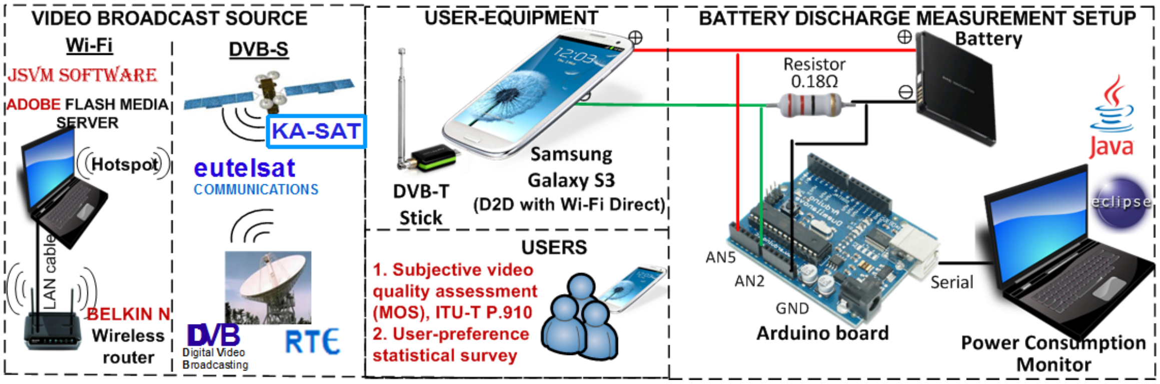


Fig. 2: Experimental setup to study UE energy consumption while receiving adaptive multimedia broadcast.

TABLE II: Frameworks for energy-efficient and QoE-aware DTV services in NGN.

| Attribute | Centralized framework | Distributed framework |
|---|---|---|
| Key features for energy-efficient and QoE-aware DTV broadcast implementation | • Broker governs the following at system-wide level<br>– Adaptive resource allocation<br>– Service pricing policy<br>• Adaptive/scalable multimedia transmission depends on heterogeneous user distribution in the entire system<br>• Broker controlled participation of Wi-Fi hotspots and D2D UEs | • Each BS and AP individually controls the following in its coverage region<br>– Adaptive resource allocation<br>– Service pricing policy<br>– Adaptive/scalable multimedia transmission<br>• Local optimization by each entity (BS, AP, hotspot, D2D UEs) for its subset of customers is possible<br>• Distributed and dynamically controlled participation of Wi-Fi hotspots and D2D UEs |
| Heterogeneous network solutions | • Third-party data offloading using centralized broker [13]<br>• Joint subchannel allocation for femtocell deployment in macrocell network [14] | • Optimal distributed network selection scheme considering multimedia application layer QoS [15]<br>• User-centric multimedia broadcast based on Bertrand duopoly equilibrium [9]<br>• Distributed resource and power allocation [16] |
| Advantages | • Easy system upgrades<br>• Centralized monitoring, maintenance, and restoration<br>• More robust optimization of resources, central entity can have high processing capability<br>• Can check compliance by multiple entities, give incentives or penalize accordingly | • Responsive to instantaneous changes in network<br>• More robust and resilient to failures<br>• Localized optimization for subset of network entities as per need is possible |
| Disadvantages | • Susceptive to failure and attacks (man-in-the middle)<br>• Do not adapt well to instantaneous network changes | • Failures can propagate across system<br>• Convergence and compliance checking not easy |
| Essential factors | • Instantaneous feedback overhead<br>• Dynamic system equilibrium sustenance<br>• Resilience against outage on central entity failure<br>• Scalability, solution complexity, and convergence | • Local equilibrium (optimization) should result in global system equilibrium<br>• Backward induction approach should be used to study the system equilibrium behavior<br>• Propagation of system failure should be checked<br>• Scalability, solution complexity, and convergence |

### B. *Adaptive hybrid architecture for DTV broadcast in NGN*

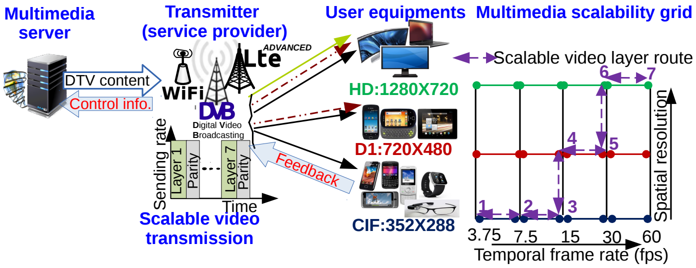
The proposed hybrid architecture for energy-efficient and QoE aware adaptive multimedia broadcast services in heterogeneous networks is depicted in Fig. 3(b). A hybrid mode would involve central control over pricing policy by a third party entity (broker). However, the network resource allocation and adaptive multimedia transmission (time-slicing or time-frequency resource allocation) is performed periodically at each BS (DVB broadcast station or eNodeB), AP, and hotspot for the subset of subscribers served by each of them. The adaptive DTV hybrid architecture supports Wi-Fi devices to be configured in D2D, multihoming, or Wi-Fi hotspot mode, in order to increase energy-efficiency, improve QoE, and serve more customers.

## IV. CROSS-LAYER ADAPTIVE BROADCAST PERFORMANCE

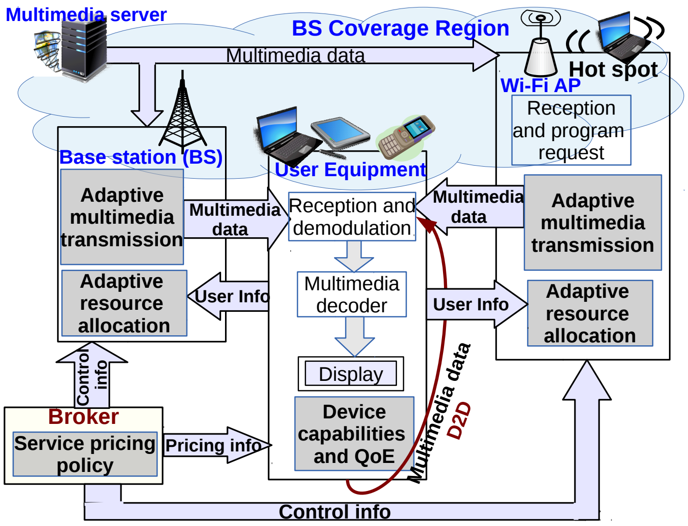
### A. *Impact of transmission technology*

Based on battery discharge experiments conducted on smart phones, Figs. 4(a)-(b) show the average battery energy discharge and average QoE in terms of MOS when using Samsung Galaxy mobile, during local playback and while receiving the scalable video content over Wi-Fi or DVB network. Similar results are observed with other devices, namely, Samsung Galaxy note, Samsung Galaxy Tab, Sony Ericsson Xperia.

It is noted from Figs. 4(a)-(b) that, on average 27.39% of energy is used up in video playback, while 30.59% and 72.03%



(a) Cross-layer adaptive DTV broadcast system



(b) Hybrid architecture for cross layer adaptive DTV over NGN

Fig. 3: (a) Cross-layer adaptive DTV broadcast; (b) Adaptive hybrid architecture for energy-efficient and QoE aware DTV over NGN.

of energy is consumed in reception over Wi-Fi and DVB network, respectively. This indicates that, wireless technology for multimedia broadcast reception impacts the UE energy consumption and hence battery life. A pairwise comparison between Wi-Fi and DVB based DTV over 10 iterations on each test device has consistently shown a lower energy consumption over Wi-Fi with a 95% confidence interval (standard deviation $\leq$ 0.02). Statistical coherence (equal variance) of the experimental results in Figs. 4(a) and 4(b) is verified with a 95% confidence interval (standard deviation $\leq$ 0.02) by performing F-test and T-test. Also, on average a higher resolution video content (D1) consumes 7.35% and 5.91% more energy than lower resolution (CIF) content reception over Wi-Fi and DVB, respectively. In terms of perceived video quality (MOS), scalable video (encoded in Scalable High efficiency Video Coding (SHVC) format) at 30 fps (frame per second) and $QP = 15$ (quantization granularity measure) has an 'excellent' video quality for both low as well as high resolution levels (i.e., CIF and D1), while the other video encoding levels in Fig. 4(b)-(c) have a 'good' video quality.

UE battery energy consumption experiments have also been conducted for DTV reception via D2D, hotspot, and AP. Corresponding energy consumption results for the various DTV scalability levels (1 through 7, indexed in Fig. 5(a)) are shown in Fig. 4(c). Statistical similarity has been ensured between the samples of DTV reception via D2D, hotspot, and AP with a high level of confidence, i.e. 95% with a standard deviation less than 0.02. It is seen that D2D based DTV reception results in least amount of UE energy consumption. Also, the energy consumption varies based on DTV content scalability level, for each of the Wi-Fi configuration modes. The extent of UE energy discharge depends on the amount of video data that is received and processed (decoded) by the UE for a specified scalability level. The scalability levels 4 and 5 are for D1 resolution at 15 and 30 fps, respectively, with equivalent amount of video data being received and decoded. Similarly, the scalability levels 6 and 7 are for HD resolution at 30 and 60 fps, respectively, with equivalently added amount of video data. Hence, as noted in Fig. 4(c), the increase in energy consumption is gradual for increased scalability levels. Hence, the features like dynamic Wi-Fi device participation (D2D, hotspot, and AP) and adaptive/scalable DTV content transmission make this proposed architecture futuristic, adaptive, and suitable for DTV services over NGN in true sense.

Some of the important observations based on these experiments are: 1) UE display energy consumption (shown as local *'playback'* results in Fig. 4(a)-(b)) and MOS depend on the video encoding level (quantization granularity, spatial resolution, and frame rate)); 2) UE energy consumption for receiving the multimedia content is strongly dependent on the wireless technology and configuration (such as, D2D, via-hotspot, or via AP, in case of Wi-Fi). Adaptive cross-layer solution for multimedia broadcast leverages these features.

### B. *Inherent trade-offs and impact of video scalability*

Based on the scalable video layer route shown in Fig. 5(a), HD video is encoded as per the SHVC standard using SHM 4 [10] encoder. Fig. 5(a) shows the trade-off between video rate and MOS for the given video layers at various QP levels. It is observed that MOS increases with increase in video rate and stabilizes at higher scalability levels of video for a given QP value. Intuitively, the video rate and MOS values decrease as QP increases. Fig. 5(b) shows the trade-off between UE energy saving by time-sliced DVB transmission and MOS for the given video layers at various QP levels. Energy saving is higher at lower QP values. Also, energy saving decreases for video layers with higher MOS for a given QP value.

The average price, determined using differential pricing model given in (1) for video layers 1 through 7, and the corresponding MOS values are shown in Fig. 5(c). The price increases with an increase in quality of video delivered (MOS value) at a given QP value. Various video scalability levels deliver specified quality levels at different prices. For example, the price for excellent quality (MOS $\geq 4.5$) video delivery at QP $= 20$ and scalability level $\geq 3$ is higher than that with QP $= 25$ and scalability level $\geq 5$. The average user preference level (defined in Table I, obtained based on study in [8]) for these video layers is based on the UE battery energy saving and MOS values of the video layers, and is shown in Fig. 5(d). It is seen from Fig. 5(d) that, the video layers are preferred (i.e., they have 'Preferred' to 'Most preferred' user preference level) when the associated MOS is $>$ 3.5 (i.e., they offer 'Good' to 'Excellent' video quality) and the corresponding

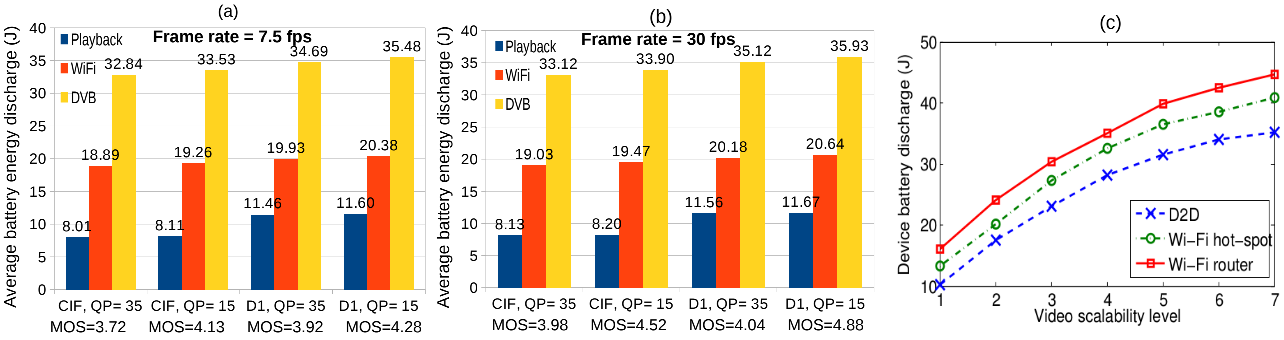


Fig. 4: (a) UE energy discharge and QoE at 7.5 fps video; (b) UE energy discharge and QoE at 30 fps; (c) UE energy discharge for D2D, Wi-Fi hotspot, and Wi-Fi router based scalable DTV reception (scalability levels 1 through 7, indexed in the grid is shown in Fig. 3(a)).

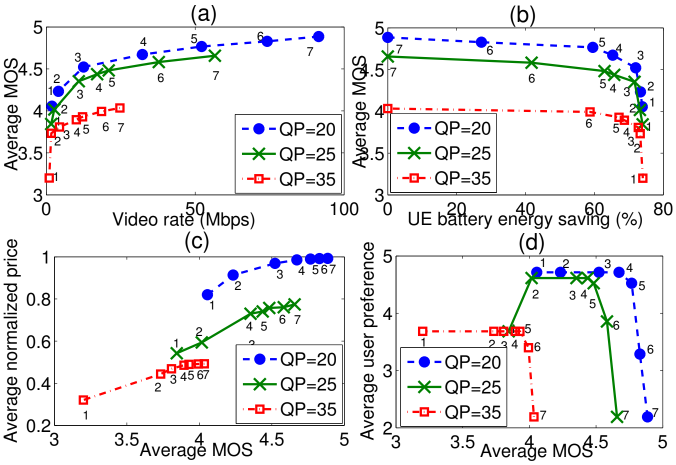


Fig. 5: (a) MOS - video rate trade-off; (b) QoE - energy trade-off; (c) DTV service price to heterogeneous users; (d) user preference (based on MOS, price, and energy saving) for scalable video layers.

UE energy saving offered is $> 40\%$. It is observed that the video layers that offer low UE energy saving in the time-sliced DVB transmission framework are less preferred, in spite of the associated higher MOS values. (For example, scalable video layer '7' has MOS$>$ 3.5 but is 'Not at all preferred' because it offers negligible UE energy saving.) This study is critical in understanding the impact of user preferences for scalable video broadcast reception on battery-limited UEs. This also helps the service provider in predicting subscriber preferences and thereby adapting the multimedia broadcast content in order to improve overall QoE.

Overall, this cross layer adaptive DTV broadcast framework ensures that diverse customers receive the multimedia content by an energy-efficient mechanism of time-sliced transmission, at QoE levels suitable to their UE battery and display constraints, and at prices in accordance with their preferences as well as the received DTV service (video quality and regular or premium service type).

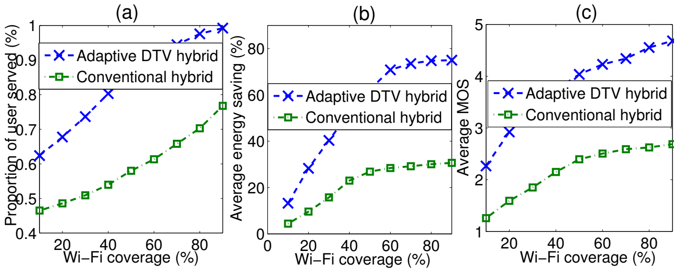


Fig. 6: Effect of Wi-Fi coverage on: (a) proportion of users served, (b) UE energy-saving, and (c) QoE performance (MOS), of adaptive DTV hybrid framework and conventional hybrid scheme [11].

## *C. Hybrid architecture system-level performance*

The energy-efficiency and QoE performance of *adaptive DTV hybrid* architecture (shown in Fig. 3(b)) in comparison with the *conventional hybrid* scheme [11] is studied in a uniformly random deployment scenario within a DVB cell (BS coverage area) with 1000 users having random device types and service requests. Standard system parameters for DVB and Wi-Fi network [9] are considered for the performance study. The comparative results on proportion of heterogeneous customers served, energy-efficiency (i.e., UE energy saving) and QoE (indicated by MOS), are shown in Figs. 6(a), 6(b), and 6(c), respectively. The proportion of customers served, energy-efficiency, and QoE, improve with increasing Wi-Fi coverage for both schemes. However, the adaptive DTV hybrid framework results in more customers getting served (on average 30.49%), higher energy-efficiency (on average 59.64% more UE energy saving), and improved QoE (on average 42.63% higher MOS) as compared to the conventional scheme. In comparison with the conventional scheme, dynamic participation of Wi-Fi devices as D2D UEs and hotspots, along with adaptive/scalable DTV content transmission over heterogeneous wireless networks, results in superior performance (in terms of QoE, energy-efficiency, and number of customers served) of the proposed adaptive hybrid DTV architecture.

Thus, the adaptive DTV hybrid framework results in a significantly higher energy saving and improved QoE, while serving a higher number of heterogeneous customers in comparison with the conventional non-adaptive broadcast scheme for multimedia broadcast in NGN.

## V. CONCLUDING REMARKS

Rapidly-evolving Information and Communication Technology (ICT) industry has led to a remarkable and powerful service-oriented revolution. The smart mobile devices with advanced processing, communication, and display capabilities have become increasingly powerful and affordable. This has led to a significant growth in the user interest. At the same time, wide range of services, e.g., social websites, mobile TV, banking, gaming, and other entertainment services, are increasingly being launched. Such massively-growing services, especially the ones based on interactive multimedia (HD TV, 3D TV), put pressure on both content processing and delivery. From the network providers' perspective, there are a wide range of technologies (e.g., LTE, Wi-Fi) that enable Internet connectivity and access to the mobile user for various services (e.g., DVB-T2, DVB-H) from anywhere at any time, which they aim to exploit for their revenue. The users on the other hand look for energy efficiency and cost for availing the broadcast/multicast services at certain desired quality. Current research efforts include such optimization strategies in finding sustainable solutions in diverse areas of ICT.

In this context, this article has discussed energy-efficient and QoE-aware adaptive multimedia content delivery solutions with differential pricing models for DTV broadcast service over heterogeneous environments to diverse users. The end-users vary in terms of device display capability, limited battery, price sensitivity, and usage context. In this regard, the article has identified the main challenges and the associated constraints for broadcast transmissions. A comprehensive overview on the various system configurations has been presented. Furthermore, through representative experimental and architecture-level simulation studies, it has been demonstrated how the adaptive strategies can address energy saving, QoE enhancement, and user price sensitivity for multimedia broadcast and multicast transmission to heterogeneous users in future heterogeneous wireless networks.

As an extension to the discussion in this article, future research needs to focus on dynamic participation and configuration selection of network entities based on the transmission energy consumption and pricing/revenue models. Furthermore, adaptive strategies of network selection by users based on DTV service quality and technology selection by network providers based on spectrum availability, needs to be studied.

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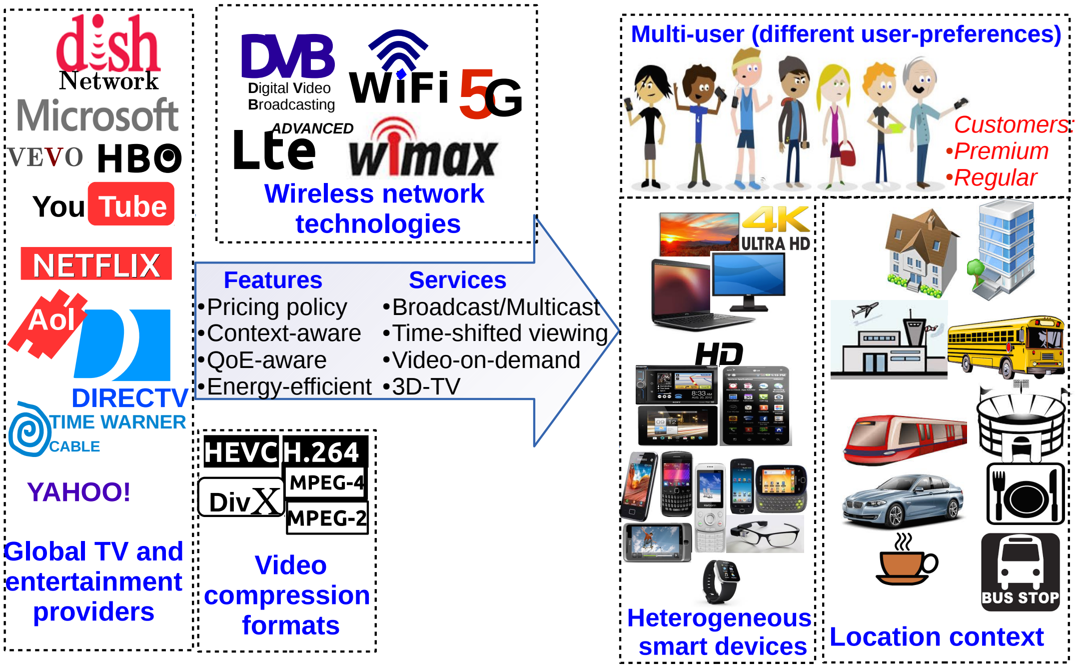


Fig. 1: Heterogeneous multimedia environment.

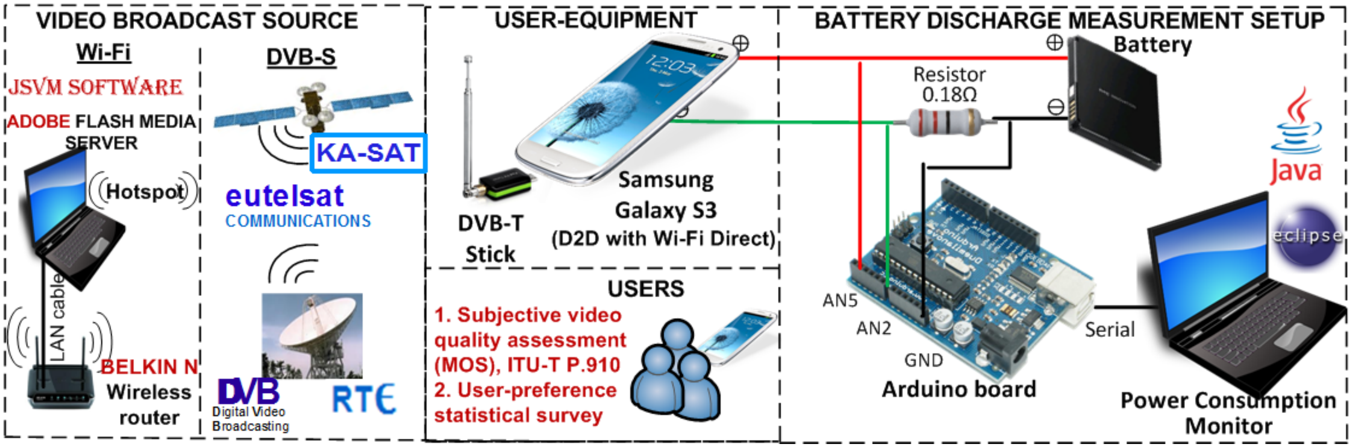
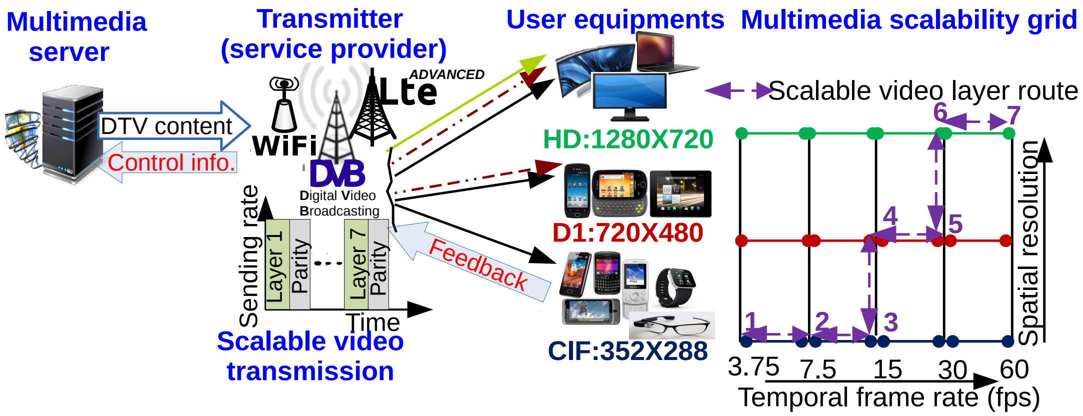
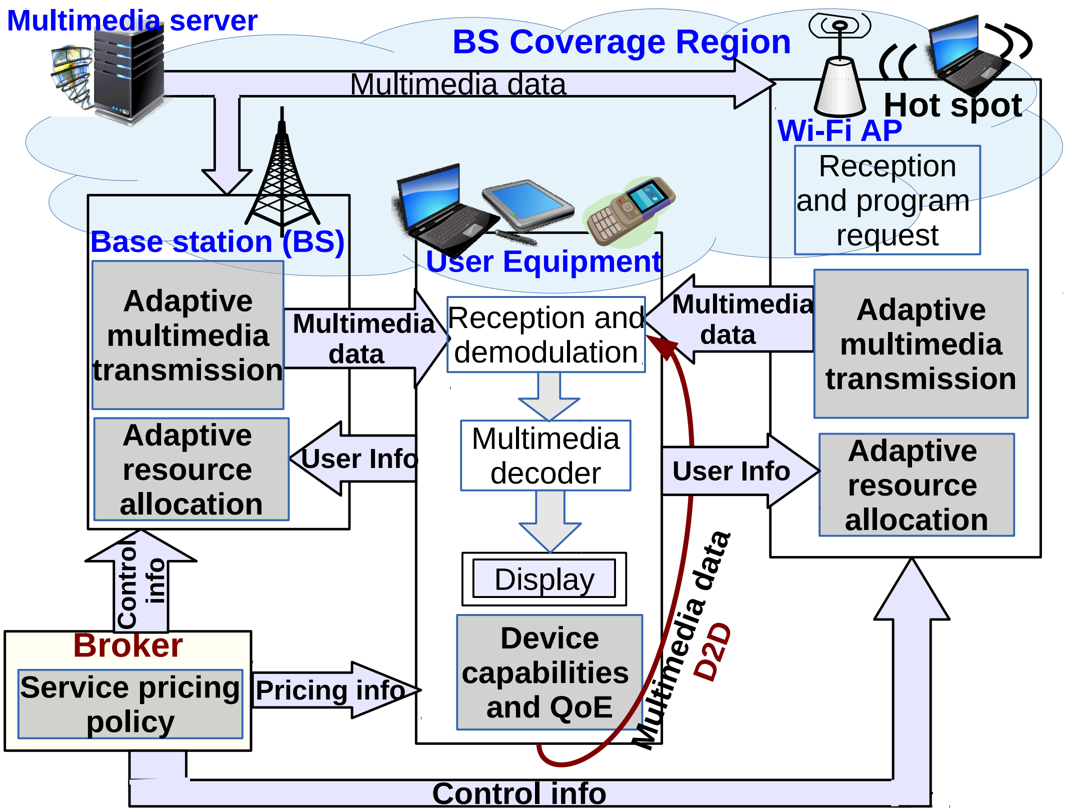


Fig. 2: Experimental setup to study UE energy consumption while receiving adaptive multimedia broadcast.



**(a) Cross-layer adaptive DTV broadcast system**



**(b) Hybrid architecture for cross layer adaptive DTV over NGN**

Fig. 3: (a) Cross-layer adaptive DTV broadcast; (b) Adaptive hybrid architecture for energy-efficient and QoE aware DTV over NGN.

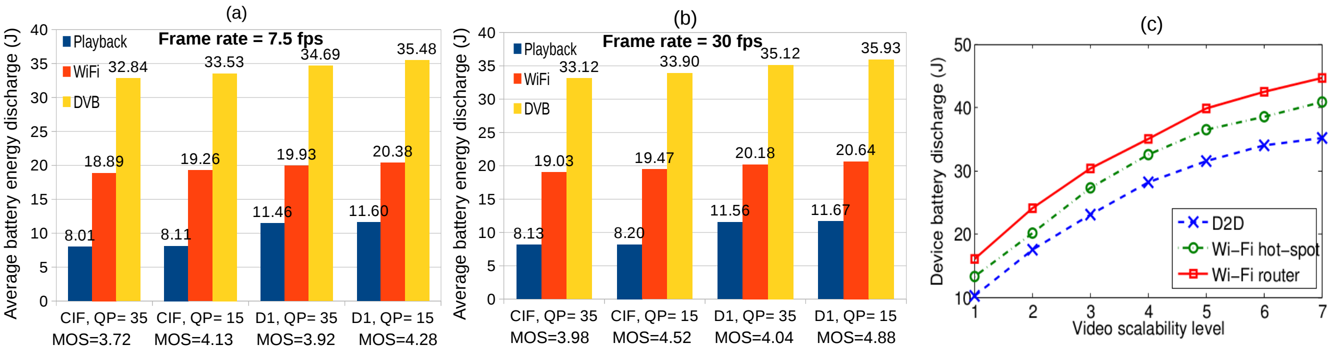


Fig. 4: (a) UE energy discharge and QoE at 7.5 fps video; (b) UE energy discharge and QoE at 30 fps; (c) UE energy discharge for D2D, Wi-Fi hotspot, and Wi-Fi router based scalable DTV reception (scalability levels 1 through 7, indexed in the grid is shown in Fig. 3(a)).

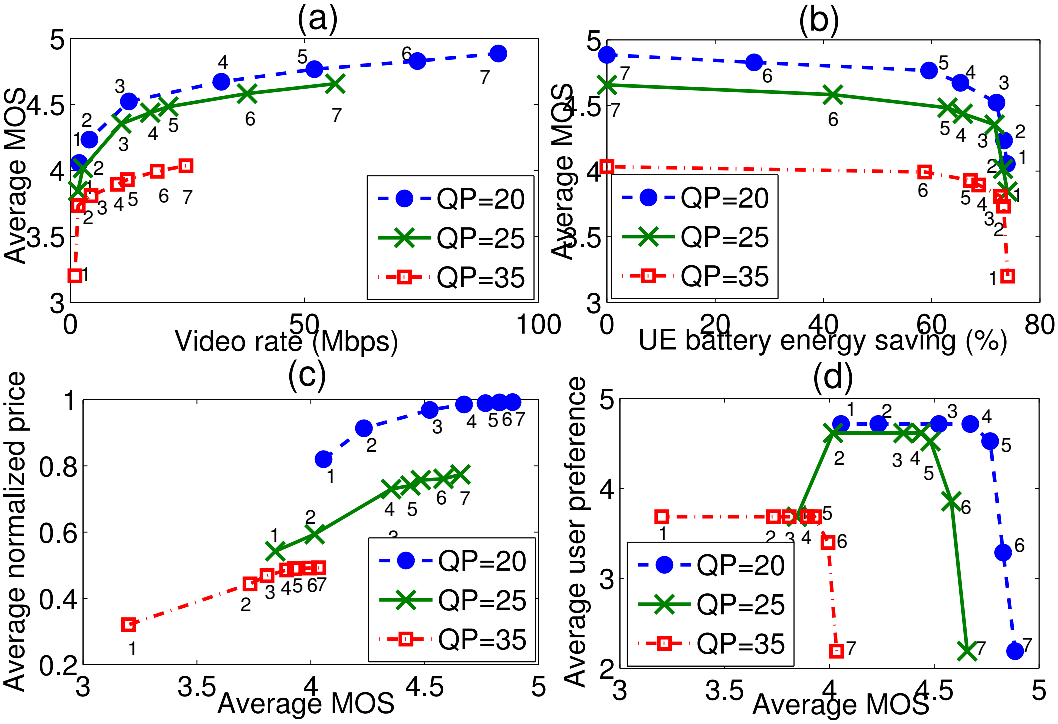


Fig. 5: (a) MOS - video rate trade-off; (b) QoE - energy trade-off; (c) DTV service price to heterogeneous users; (d) user preference (based on MOS, price, and energy saving) for scalable video layers.

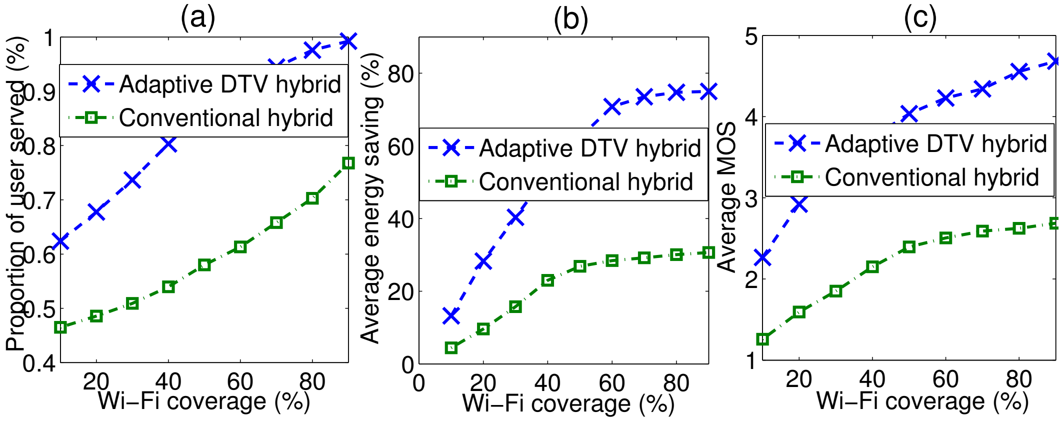


Fig. 6: Effect of Wi-Fi coverage on: (a) proportion of users served, (b) UE energy-saving, and (c) QoE performance (MOS), of adaptive DTV hybrid framework and conventional hybrid scheme [11].