An Efficient Live TV Scheduling System for 4G LTE Broadcast

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Abstract—Traditional live television (TV) broadcasting systems are proven to be spectrum inefficient. Therefore, researchers propose to provide TV services on fourth-generation (4G) long-term evolution (LTE) networks. However, static broadcast, a typical broadcasting method over cellular network, is inefficient in terms of radio resource usage. To solve this problem, the audience-driven live TV scheduling (ADTVS) framework is proposed, to maximize radio resource usage when providing TV broadcasting services over LTE networks. ADTVS, a system-level scheduling framework, considers both available radio resources and audience preferences, in order to dynamically schedule TV channels for broadcasting at various time and locations. By conducting a simulation using real-life data and scenarios, it is shown that ADTVS significantly outperforms the static broadcast method. Numerical results indicate that, on average, ADTVS enables substantial improvement to broadcast efficiency and conserves considerable amount of radio resources, while forgoing less than 5% of user services compared to the benchmark system.

Index Terms—Broadcast, evolved multimedia broadcast multicast service (eMBMS), long-term evolution (LTE), resource allocation, resource scheduling, television (TV).

I. INTRODUCTION

TRADITIONAL television (TV) has been broadcast in dedicated systems, such as terrestrial TV and satellite transmission. However, these traditional systems solely provide TV service, limiting the usage of radio resources and flexibility of frequency spectrum. Recent research shows that traditional TV broadcast with high radiated power is spectrum inefficient [1]. These systems require a frequency spectrum three times wider than that of mobile cellular network to cover the same area. Moreover, they are targeted for static home users but not mobile devices. The widely deployed long-term evolution (LTE) network is a potential alternative to TV broadcasting services. LTE is a fourth-generation (4G) mobile phone communications and Internet access standard that is equipped with high system capacity and transmission rate. It fulfills the requirements of broadcasting high-quality TV contents. The flexibility of radio resources allocation enables dynamic allocation of frequency spectrum to unicast or multicast/broadcasting services. Furthermore, a variety of broadcasting services can be deployed in different areas with various strategies on associated base station (BS).

The current LTE evolved multimedia broadcast multicast service (eMBMS) service does not explicitly define the scheduling of broadcasting TV channels. It gives a higher degree of freedom to commercial operators to define their own broadcasting strategies according to individual situation. Without a dynamic broadcasting strategy, the typical approach for broadcasting TV channels over cellular networks is static broadcast method [2], [3]. In this approach, BSs continuously broadcast all TV channels. However, this approach has several drawbacks. First, broadcast efficiency decreases with greater divergence of TV popularity. Apparently, allocating the same amount of resources to TV channels with different numbers of audiences, neglecting the difference in demand, decreases the efficiency of broadcasting [2]. Second, broadcast efficiency is reduced when TV audiences' size grows or shrinks in size at different times of a day. This requires an adaptive allocation of resources. In particular, broadcast efficiency is lowered tremendously when the same amount of resources is allocated to off-peak as peak hours. Third, spectrum efficiency is lowered when there is only a few or no audience, under a BS coverage [4]. This problem becomes even worse in sparsely populated areas. Fourth, in some cases, the bandwidth provided is not sufficient to support a large number of TV channels. In addition, cable TV providers are offering hundreds of TV channels simultaneously to audiences, whereas the available frequency bandwidth of a mobile network operation is limited. Thus, it is difficult to support such a large number of TV channels. Therefore, a smart dynamic TV scheduling framework is required to maximize radio resource usage.

In this paper, the above drawbacks have been addressed by proposing a system-level framework, audience-driven live TV scheduling (ADTVS). This schedules radio resources for broadcasting live TV channels through LTE network by considering user preferences, time, and location. ADTVS aims to increase broadcast efficiency while limiting the number of unserved users. Three algorithms are developed for estimating available radio resources in BSs, measuring popularity of TV channels, and allocating radio resources to TV channels for broadcasting. Moreover, two schemes are proposed for dynamically assigning input parameters of ADTVS, suboptimal and optimal schemes. The suboptimal scheme is straightforward with low complexity while achieving high broadcast efficiency. In the optimal scheme, the scheduling problem is formulated as a mixed-integer optimization problem and is solved with the genetic algorithm. In order to demonstrate the effectiveness of the proposed framework, real-life data are gathered from TV audience reports, real geographical location, and real BS deployment. Three metrics are used to evaluate the framework performance,

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namely broadcast efficiency, conserved throughput, and the number of served users. The framework is evaluated against benchmark static broadcast method.

The contributions of this paper are fourfold as follows. This is apparently the first framework of TV scheduling in LTE network proposed based on user preferences, which also introduces a new perspective of allocating radio resources. Moreover, the available resources, which are the number of subframes and throughput, are carefully estimated for broadcasting from the standard LTE physical (PHY) layer. Third, the genetic algorithm is used to numerically address the mixed-integer optimization problem, essentially for finding the optimal input parameters of the scheduling problem. Finally, the framework is evaluated by comparing it with static broadcast method using real-life data.

This paper is organized as follows. Section II introduces the background of LTE. The two schemes are described in Section IV as they dynamically assign input parameters of ADTVS. Section V explains the sources of the real-life data and the assumptions made for the simulation. The evaluation and discussion for future research are presented in Sections VI and VII. Finally, conclusion is made in Section VIII.

II. BACKGROUND

In this section, a detailed technical overview of the technologies used by the ADTVS framework is presented.

A. Evolved Multimedia Broadcast Multicast Service

In order to provide efficient broadcast and multicast services, MBMS is designed as a point-to-multipoint interface specification for third generation partnership project (3GPP) cellular networks. It defines configuration for broadcasting services in the core and the radio access networks. Single-frequency network (SFN) configuration is defined in MBMS for broadcasting transmission across multiple cells. eMBMS is a LTE advanced (LTE-A) specification announced in LTE Release 9 to provide efficient delivery of broadcast and multicast services [5]. The performance is improved by higher bitrates and more flexible carrier configuration. It supports broadcasting transmission across multiple cells. It is designed for broadcasting applications.

The major components of eMBMS include broadcast/multicast service center (BM-SC), MBMS gateway (MBMS-GW), mobility management entity (MME), multicell/multicast coordinating entity (MCE), and e-UTRAN NodeB (eNB). BM-SC announces broadcasting services to end users. It is an entry point for content providers transmitting content from external networks to mobile network. MBMS-GW is a logical node for broadcasting user plane data to eNB, which is the name of BS in LTE, within the service area. It sends MBMS session control signals to the MME. MCE performs admission control, allocation of radio resources throughout MBMS session control signals. The eNB is used for data distribution to end users [6].

Fig. 1 shows the LTE protocol architecture. Multicast control channel (MCCH) and multicast traffic channel (MTCH) are defined as logical channels at media access control

Fig. 1. MBMS protocol layers.

(MAC) layer. These are the data entry points from the radio link control (RLC) layer. MCCH is a control channel that used to transmit control information for MBMS reception. MTCH is used for downlink data transmission of MBMS services. MCCH and MTCH are multiplexed into multicast channel (MCH) for scheduling and transport format configuration. The processes of coding, modulation, and related PHY layer operations are performed in PHY layer and the corresponding data output are sent out through physical MCH (PMCH) [7].

Multiple eNBs are joined together to form an MBMS SFN (MBSFN). The signals which is broadcast from different eNBs in the MBSFN are synchronized and identical, using the same subframes, and the same modulation and coding scheme (MCS). From the receiver's point of view, the received signal is similar to the signal transmitted from a single BS but passes through a multipath channel, in a result of a time-dispersive signal. This turns the cell edge destructive interferences into a constructive aggregated signal. The received signal quality and spectral efficiency are improved by this method. MCE manages the services of MBSFN area, controlling time synchronization, and radio resources allocation. Multiple eNBs within an MBSFN are connected to the same MCE which controls one or multiple cells [8].

B. eMBMS Configuration

The following configuration is specified for eMBMS and related components. MTCH is transmitted by RLC unacknowledged mode which has no feedback in uplink from user equipments [9]. Maximum of 6 out of 10 subframes from a physical radio frame can be configured as MBSFN subframe in frequency-division duplex (FDD) mode. In time-division duplex (TDD) mode, only 5 out of 10 subframes can be configured as MBSFN subframe. The common subframe allocation (CSA) is periodic, which determines the number of subframes for MBSFN in one period. The period is varied from 1 to 32 frames [10]. PMCH uses the same scheme as physical downlink shared channel (PDSCH) for determining the modulation and transport block size [9]. Modulation for PMCH can be QPSK, 16 QAM, and 64 QAM. It has no transmit diversity which means that only a single antenna is used for transmission, layer mapping, and precoding. It uses antenna port 4 for transmission which is dedicated for MBSFN subframe without other kinds of traffic, such as, unicast [11]. MBSFN has its own reference signal transmitted in MBSFN region.

C. Resource Structure

The transmission scheme of LTE adopts orthogonal frequency-division mutiplexing (OFDM). In this technology,

Fig. 2. eMBMS resource grid.

radio resources are allocated in time and frequency domains. In general, the time–frequency structure for transmitting eMBMS traffic is slightly different from the unicast traffic. In time domain, a single frame has ten subframes. The length of each subframe is 1ms. A subframe has two slots, each of them is 0.5ms. In order to provide SFN transmission with long delay spread, extended cyclic prefix is used for MBSFN transmission. Therefore, a single slot has only six symbols, whereas in normal cyclic prefix configuration, each slot has seven symbols. In frequency domain, each subcarrier spacing is defined as 15kHz. Fig. 2 shows an example of radio resource structure in time and frequency domain. The minimum physical layer resource is a resource element. It consists of one subcarrier and one OFDM symbol. A resource block is defined as 12 consecutive subcarriers and 1 slot. In extended cyclic prefix configuration, there are 6 symbols $\times$ 12 subcarriers, which are 72 resource elements in one resource block [11].

III. ADTVS SYSTEM FORMULATION

In this section, the system formulation is presented. ADTVS schedules TV channels to be broadcast according to audience preferences and location in LTE network. The design of ADTVS complies with the LTE standard.

The following variables and parameters are defined before presenting the main algorithms. Let i be the index of time segments for a day. Let $\mathcal{J}$ be the set of cells in the region and j be the index of cells. Let $\mathcal{K}$ be the set of TV channels that are being selected for broadcasting and indexed by k_m . Let $\mathcal{Q}_{ij} \subseteq \mathcal{K}$ be the set of selected TV channels by ADTVS to be broadcast in time segment i at cell j . In each time segment i at each cell j , $|\mathcal{Q}_{ij}|$ out of $|\mathcal{K}|$ TV channels are selected for broadcasting, which implies that $0 \leq |\mathcal{Q}_{ij}| \leq |\mathcal{K}|$. The set $\overline{\mathcal{Q}_{ij}}$ is defined as the complement of $\mathcal{Q}_{ij}$ such that $\mathcal{Q}_{ij} \cup \overline{\mathcal{Q}_{ij}} = \mathcal{K}$. The other model parameters are listed in Table I.

In the proposed framework, the following algorithms are introduced. Algorithm 1 is the main algorithm, which consists of Algorithms 2–4. It is executed in every time segment i for each cell j in MCE. The time length of a TV program is typically range from half an hour to two hours. Therefore, setting the length of each time segment from 15 min to 1 h is comparable to most of the TV programs. Algorithm 2 estimates available resources. Algorithm 3 measures popularity of TV channels according to user preferences. Algorithm 4 allocates available radio resources to popular TV channels for broadcasting. These algorithms are considered as an extension to

TABLE I
MODEL PARAMETERS

Symbols	Descriptions
α_{ij}	Frame allocation period; $\alpha_{ij} \in \{1, 2, 4, 8, 16, 32\}$
β_{ij}	MCS index; $\{\beta_{ij} \in \mathbb{Z} : 0 \leq \beta_{ij} \leq 28\}$
γ_{ij}	The number of subframes assigned for MBSFN per α_{ij} in time domain; $\{\gamma_{ij} \in \mathbb{Z} : 0 \leq \gamma_{ij} \leq 24\}$
$R_{ij}^a(\alpha_{ij}, \beta_{ij}, \gamma_{ij})$	Simplified as R_{ij}^a , maximum allowed throughput in bit per second for broadcasting at time i in cell j
D	Duplex mode; $D \in \{\text{'TDD'}, \text{'FDD'}\}$
w	Frequency bandwidth (MHz)
S_{ij}^m	Subframe allocation mode; $S_{ij}^m \in \{1, 4\}$
S_{ij}^b	Subframe allocation bitmap; $S_{ij}^b = \{b_1, \dots, b_u, \dots, b_U : \forall u \in \mathbb{Z}, b_u \in \{0, 1\}\}$ If $S_{ij}^m = 1, U = 6$; If $S_{ij}^m = 4, U = 24$
o	Overhead parameter, $o = (0, 1)$
b_{ij}^s	Transport block size at time i in cell j (bits)
b_{ij}^a	Available number of bits per allocation period at time i in cell j
$P_{ij}(c)$	Popularity of TV channel c at time i in cell j
$\mathcal{K}$	The set of TV channels that are being selected for broadcasting. The elements of $\mathcal{K}$ are defined as $\{k_m \in \mathcal{K} \forall m \in \mathbb{Z} : 1 \leq m \leq \mathcal{K} \}$
$\mathcal{L}_{ij}$	A list of sorted TV channels according to popularity in descending order at time i in cell j . The elements of $\mathcal{L}_{ij}$ are defined as: $\{l_{ijp} \in \mathcal{L}_{ij} \forall p \in \mathbb{Z} : 1 \leq p \leq \mathcal{K} , \dots, P_{ij}(l_{ij1}) \geq \dots \geq P_{ij}(l_{ijn}) \geq \dots \geq P_{ij}(l_{ij \mathcal{K} })\}$
$\mathcal{Q}_{ij}$	The set of selected TV channels that being broadcast at time i in cell j . $\mathcal{Q}_{ij} \subseteq \mathcal{K}$, $\mathcal{Q}_{ij} \subseteq \mathcal{L}_{ij}$ The elements of $\mathcal{Q}_{ij}$ are defined as $\{q_{ijn} \in \mathcal{Q}_{ij} \forall n \in \mathbb{Z} : 1 \leq n \leq \mathcal{Q}_{ij} \leq \mathcal{K} \}$
$R(c)$	Required bitrate to broadcast channel c in a cell
R_{ij}^c	The total consumed throughput for broadcasting TV channels at time i in cell j . $R_{ij}^c = \sum_{c \in \mathcal{Q}_{ij}} R(c)$
R^b	Total throughput for static broadcast in a cell
N_{ij}	The number of total users at time i in cell j
$N_{ij}^d(c)$	The number of historical audiences of channel c from statistical data at time i in cell j
$N_{ij}^w(c)$	The number of watching audiences of channel c that is broadcast at time i in cell j .
N_{ij}^s	The number of served users at time i in cell j .

Algorithm 1. Audience Driven Live TV Scheduling

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for  $i \leftarrow$  each time segment do
  for  $\forall j \in \mathcal{J}$  do
    Run Algorithm 2 for estimating available radio resources
    Run Algorithm 3 for measuring TV channels popularity
    Run Algorithm 4 for allocating radio resources to popular channels for broadcasting
  end
end

```

the existing LTE entities described in the previous section. Fig. 3 shows the proposed algorithms within the MBMS logical architecture.

Available resources are estimated as maximum allowed throughput R_{ij}^a by Algorithm 2. The algorithm takes various system parameters into account, including duplex mode D , frequency bandwidth w , radio frame allocation period α_{ij} , MCS index β_{ij} , subframe allocation mode S_{ij}^m , and subframe allocation bitmap S_{ij}^b . Each of the possible values of frame allocation period $\alpha_{ij} \in \{1, 2, 4, 8, 16, 32\}$ corresponds to $\{10, 20, 40, 80, 160, 320\}ms$, respectively. The number of resource blocks $n_{rb}(w)$ is first obtained according to w . Then,

Algorithm 2. Available Resources Estimation Algorithm

input : Duplex Mode, D
Frequency Bandwidth (MHz), w
frame allocation period (# of frames), α_{ij}
MCS index, β_{ij}
Subframe allocation mode, S_{ij}^m
Subframe allocation bitmap, S_{ij}^b

output: R_{ij}^a
Time per frame, $t_f = 10\text{ ms}$;
Overhead parameter in percentage, o ;

Switch w **do** Assign number of resource blocks in freq. domain,
 $n_{rb}(w)$ according to w
 case 1.4, $n_{rb}(w) = 6$;
 case 3, $n_{rb}(w) = 15$;
 case 5, $n_{rb}(w) = 25$;
 case 10, $n_{rb}(w) = 50$;
 case 15, $n_{rb}(w) = 75$;
 case 20, $n_{rb}(w) = 100$;
endsw
 $\gamma_{ij} = f_{\gamma_{ij}}(D, S_{ij}^m, S_{ij}^b)$;
if $\beta_{ij} \leq 9$ **then**
 $I_t(\beta_{ij}) = \beta_{ij}$;
else if $\beta_{ij} \leq 16$ **then**
 $I_t(\beta_{ij}) = \beta_{ij} - 1$;
else if $\beta_{ij} \leq 28$ **then**
 $I_t(\beta_{ij}) = \beta_{ij} - 2$;
end
 $b_{ij}^s = f_{b_{ij}^s}(n_{rb}(w), I_t(\beta_{ij}))$;
 $b_{ij}^a = b_{ij}^s \times \gamma_{ij}$;
 $R_{ij}^a = (1 - o) \times b_{ij}^a / (\alpha_{ij} \times t_f)$;

Algorithm 3. Popularity Measurement of TV Channels Algorithm

input : TV statistical data with locations and channels grouped by time segment

output: sorted TV channels list $\mathcal{L}_{ij}$ at time i in cell j

for $\{k_1, k_2, \dots, k_m, \dots, k_{|\mathcal{K}|}\} \in \mathcal{K}$ **do**
 Popularity $P_{ij}(k_m) = N_{ij}^d(k_m)$;
end
sort the channel list according to $P_{ij}(k_m)$ in descending order and return the sorted list $\mathcal{L}_{ij}$;

γ_{ij} is obtained from a function $f_{\gamma_{ij}}(D, S_{ij}^m, S_{ij}^b)$ as described below. The duplex mode and the subframe allocation mode are sets of two elements, which are $D \in \{\text{"TDD"}, \text{"FDD"}\}$ and $S_{ij}^m \in \{1, 4\}$, respectively. There are two options for S_{ij}^b , depending on the value of S_{ij}^m . If S_{ij}^m is equal to 1, S_{ij}^b is a bitmap with length of 6 bits. If S_{ij}^m is equal to 4, the length of S_{ij}^b is 24 bits. One important note is that, if S_{ij}^m is equal to 4, α_{ij} could not be equal to 1 or 2 because the number of assigned subframes should be less than the number of total subframes in a frame allocation period. Each bit of S_{ij}^b corresponds to a subframe. "1" denotes that subframe is allocated for MBSFN and "0" is not. In FDD mode and when $S_{ij}^m = 1$, starting from

Algorithm 4. Radio Resources Allocation Algorithm

input : $R_{ij}^a, \mathcal{L}_{ij}$
 $n = 1; R_{ij}^c = 0$;
while $R_{ij}^a \geq R(l_{ijn})$ **do**
 $R_{ij}^a = R_{ij}^a - R(l_{ijn})$;
 if l_{ijn} **is broadcasting in other cells** **then**
 Assign the same resources blocks
 else
 Assign new resources blocks
 end
 Broadcast l_{ijn} ;
 $R_{ij}^c = R_{ij}^c + R(l_{ijn})$;
 $n = n + 1$;
end

Fig. 3. Proposed algorithms within the eMBMS logical architecture and the original functionalities of entities.

the first bit of S_{ij}^b , the allocation applies to subframes #1, #2, #3, #6, #7, and #8. In TDD mode and when $S_{ij}^m = 1$, the allocation applies to subframes #3, #4, #7, #8, and #9. If $S_{ij}^m = 4$, the allocation is continuous for the above-mentioned subframes in the sequence of four radio frames. By considering these configurations, γ_{ij} is obtained as an integer in a range from 0 to 24 subframes in FDD mode, or 0 to 20 subframes in TDD mode. Next, the transport block size index $I_t(\beta_{ij})$ is obtained from β_{ij} . The variables $n_{rb}(w)$ and $I_t(\beta_{ij})$ are then used to determine the transport block size b_{ij}^s , which is the maximum number of bits that are available for transmission in one subframe. The function $f_{b_{ij}^s}(\cdot)$ is constructed from the transport block size table, which is defined in [9]. The available number of bits per allocation period b_{ij}^a is obtained by multiplying b_{ij}^s and γ_{ij} . A large percentage of radio resources are consumed by overhead, such as packet headers and preamble. Therefore, the overhead parameter is defined as $o = (0, 1)$ for excluding the radio resources that are utilized by overhead. Finally, the maximum allowed throughput is calculated by dividing b_{ij}^a by the total time of a frame allocation period and excluding the resources for overhead. Because the values of the input parameters of this algorithm are bounded, and the running time of the algorithm does not depend on the size of input, the time complexity of Algorithm 2 is constant.

Algorithm 3 sorts TV channels according to their popularity. Generally, there are different ways to measure popularity of a TV channel, such as studying the viewing log at client devices, extracting data from diary records, conducting surveys, rating from audiences, and measuring the number of social recommendations and discussions of a TV program. However, for highlighting the idea of radio resource allocation, the popularity, which is $P_{ij}(k_m)$ of channel k_m at time segment i in cell j , is determined by the number of audiences [i.e., $N_{ij}^d(k_m)$] of each TV channel in various cells and time segments from statistical data. In this algorithm, the set $\mathcal{K}$ is sorted according to TV channel popularity in descending order. In the sorted list $\mathcal{L}_{ij}$ of time segment i at cell j , a set element is defined as l_{ijp} , which is the p th popular channel in the list. The first channel l_{ij1} is the most popular TV channel. Assuming that the time complexity of determining the popularity of a TV channel is constant, the time complexity of the for loop is $O(|\mathcal{K}|)$. The typical time complexity of the sorting is $O(|\mathcal{K}| \log |\mathcal{K}|)$. Therefore, the overall time complexity of Algorithm 3 is $O(|\mathcal{K}| \log |\mathcal{K}|)$, where $|\mathcal{K}|$ is the number of TV channels. The complexity may be changed if the method of determining the popularity is changed. The outputs of Algorithms 2 and 3 are utilized for radio resource allocation in Algorithm 4.

In Algorithm 4, the available radio resources R_{ij}^a , which are estimated in Algorithm 2, are allocated to popular TV channels for broadcasting. In the initialization, channel broadcasting index n is set to be 1. If R_{ij}^a is larger than or equal to the required bitrate of the most popular TV channel, which is $R(l_{ij1})$, then channel l_{ij1} (i.e., the first element in $\mathcal{L}_{ij}$) is being broadcast and the radio resources are reserved for this. Recall that receivers are benefited from the constructive aggregated broadcasting signal from multiple BSs. Therefore, the same resources' blocks in various BSs will be allocated for a TV channel. If a TV channel is not broadcasting in other cells, a new set of resources' blocks will be allocated. After the resource allocation for the current channel, n increases by 1. The process is continued until the available radio resources are less than the requirement for broadcasting the next TV channel. The time complexity of Algorithm 4 is $O(|\mathcal{Q}_{ij}|)$, where $|\mathcal{Q}_{ij}|$ is the total number of TV channels that are being broadcast.

Broadcast efficiency is related to the input parameters of Algorithm 2. Note that D is fixed for the whole operating network according to the operator configuration. The bandwidth w is usually unchanged because 4G service providers utilize the whole band of licensed spectrum. Therefore, both of these parameters are statically assigned. One of the drawbacks of the static broadcast method is to statically assign the other network parameters (i.e., α_{ij} , β_{ij} , S_{ij}^m , and S_{ij}^b), which does not smartly utilize the resources. Thus, to overcome this weakness, dynamic parameters assignment technique is proposed in the next section. A higher broadcast efficiency will be achieved if these parameters are optimally assigned.

IV. ADTVS METHODOLOGY

In this section, two schemes for dynamically assigning the input parameters of ADTVS (i.e., α_{ij} , β_{ij} , S_{ij}^m , and S_{ij}^b) are presented. These schemes are designated as suboptimal and

optimal. Adjusting these parameters leads to different R_{ij}^a at each time segment and cell.

A. Suboptimal Scheme

The principle of this scheme is to manually adjust the parameters according to the number of audiences at each time segment in each cell. Adjusting the parameters in the following ways leads to a higher R_{ij}^a . It serves more audiences, but consumes more resources.

- 1) Decrease α_{ij} for a shorter allocation period.
- 2) Increase β_{ij} for a higher order modulation and coding rate scheme.
- 3) Adjust S_{ij}^m and S_{ij}^b to obtain larger number of MBSFN subframes in an allocation period.

Operators assign these parameters to obtain suitable R_{ij}^a value for each time segment in each cell individually and independently. For instance, in off-peak hours, a lower value of R_{ij}^a is assigned to achieve a higher broadcast efficiency because of fewer audiences. In peak hours, higher value of R_{ij}^a is assigned to serve more audiences. Different R_{ij}^a values are assigned to different cells according to the number of users in cells. A higher value of R_{ij}^a is assigned for a cell with more users.

This scheme is straightforward and requires less computing power to obtain a solution. The resulting R_{ij}^a is relatively steady. However, it requires experienced operators to adjust the parameters and it is difficult to obtain an optimal solution.

B. Optimal Schemes

The purpose of optimal schemes is to obtain an optimal set of input parameters that maximizes the overall performance of a certain objective function. The objective function is the weighted sum of broadcast efficiency E_{ij} , conserved throughput C_{ij} , and the number of served users N_{ij}^s .

First, broadcast efficiency E_{ij} for each time segment i in each cell j is defined as

$$E_{ij} = \frac{\sum_{c \in \mathcal{Q}_{ij}} N_{ij}^w(c)}{R_{ij}^c} = \frac{f_w(R_{ij}^a, P_{ij})}{R_{ij}^c} \quad (1)$$

where E_{ij} measures the number of watching audiences per bit per second at each time segment i in cell j . The number of watching audiences, denoted as $f_w(\cdot)$, is a function of two parameters, available radio resources R_{ij}^a and popularity of TV channels P_{ij} .

Second, conserved throughput C_{ij} is the difference of consumed throughput between static broadcast and ADTVS, expressed as follows:

$$C_{ij} = R^b - R_{ij}^c. \quad (2)$$

Third, the number of served users N_{ij}^s is defined as the difference between the number of total users $N_{i,j}$ and the number of users of nonbroadcast TV channels. It is worth noting that N_{ij}^s includes users which are not watching TV

$$N_{ij}^s = N_{i,j} - \sum_{c \in \overline{\mathcal{Q}_{ij}}} N_{ij}^w(c) = N_{i,j} - f_u(R_{ij}^a, P_{ij}) \quad (3)$$

where $\overline{Q_{ij}}$ is the set of nonbroadcast channels. The function $f_u(\cdot)$ calculates the total number of unserved users.

Based on the selection of weights, two problem formulations are proposed to obtain optimal input variables. The first formulation $\mathcal{P}_1$ considers fixed weighting parameters a_0 , a_1 , and a_2 , over all cells and time segments. The second formulation $\mathcal{P}'_1$ adaptively optimizes the weighting variables a_{0i} , a_{1i} , and a_{2i} in each time segment to achieve an enhanced solution. Note that some parameters are not numeric, such as S_{ij}^m , S_{ij}^b , and D . They are transformed to γ_{ij} via $f_{\gamma_{ij}}(\cdot)$. The optimization variables α_{ij} , β_{ij} , and γ_{ij} are integer. Therefore, the problems are formulated as mixed-integer optimization problems.

In the first formulation, the maximization of the objective function is achieved by optimizing over α_{ij} , β_{ij} , and γ_{ij} and a fixed set of weighting parameters a_0 , a_1 , and a_2 . It is formulated as follows:

$$\mathcal{P}_1 : \max_{\alpha_{ij}, \beta_{ij}, \gamma_{ij}} a_0 \sum_{j \in \mathcal{J}} E_{ij} + a_1 \sum_{j \in \mathcal{J}} C_{ij} + a_2 \sum_{j \in \mathcal{J}} N_{ij}^s \quad (4a)$$

$$\text{subject to } \mathcal{C}_1 : R_{ij}^a \leq R^b \quad (4b)$$

$$\mathcal{C}_2 : \frac{N_{ij}^s}{N_{ij}} \geq N_c \quad (4c)$$

$$\mathcal{C}_3 : \forall e \in \mathbb{Z}, 0 \leq e_{ij} \leq e_{ij}^{ub} \quad (4d)$$

$$\mathcal{C}_4 : \forall \beta_{ij} \in \mathbb{Z}, 0 \leq \beta_{ij} \leq \beta_{ij}^{ub} \quad (4e)$$

$$\mathcal{C}_5 : \forall \gamma_{ij} \in \mathbb{Z}, 0 \leq \gamma_{ij} \leq \gamma_{ij}^{ub} \quad (4f)$$

$$\mathcal{C}_6 : N_{ij} \geq 0, R^b \geq 0. \quad (4g)$$

The maximum allowed throughput R_{ij}^a , in (4b), is limited by the total consumed throughput of static broadcast R^b . The number of served users should be larger than N_c percent of the total number of users in (4c). The variable α_{ij} , defined as $\alpha_{ij} = 2^{e_{ij}}$, is constrained in (4d) and e_{ij}^{ub} is the upper bound of e_{ij} . The upper bounds of e and frame allocation period α_{ij} are 5 and 32, respectively. The range of MCS index is defined in (4e), where $\beta_{ij}^{ub} = 28$. The allowed range for the number of subframes per allocation period γ_{ij} is specified in (4f), where the upper bound γ_{ij}^{ub} is equal to 24. The parameters are ensured to be greater than or equal to zero. The weighting parameters a_0 , a_1 , and a_2 are adjusted to change the impact of each metric in the objective function for all time segments in all cells.

In order to increase the degree of freedom, intuitively improving the performance, and highlighting the influence of each of the evaluation metrics (i.e., E_{ij} , C_{ij} , and N_{ij}^s) into the overall objective function, the second formulation is proposed. In this formulation, the weighting variables a_{0i} , a_{1i} , and a_{2i} are optimized in addition to α_{ij} , β_{ij} , and γ_{ij} . The optimized results are obtained by extending Problem $\mathcal{P}_1$ into the following problem:

$$\mathcal{P}'_1 : \max_{\alpha_{ij}, \beta_{ij}, \gamma_{ij}, a_{0i}, a_{1i}, a_{2i}} a_{0i} \sum_{j \in \mathcal{J}} E_{ij} + a_{1i} \sum_{j \in \mathcal{J}} C_{ij} + a_{2i} \sum_{j \in \mathcal{J}} N_{ij}^s \quad (5a)$$

$$\text{subject to } \mathcal{C}_1; \mathcal{C}_2; \mathcal{C}_3; \mathcal{C}_4; \mathcal{C}_5; \mathcal{C}_6 \quad (5b)$$

$$\mathcal{C}_7 : a_{0i} + a_{1i} + a_{2i} = 1 \quad (5c)$$

$$\mathcal{C}_8 : 0 \leq a_{0i}, a_{1i}, a_{2i} \leq 1. \quad (5d)$$

Algorithm 5. Genetic Algorithm

input : $R^b, N_c, \alpha_{ij}^{ub}, \beta_{ij}^{ub}, \gamma_{ij}^{ub}$

output: $\alpha_{ij}^*, \beta_{ij}^*, \gamma_{ij}^*$

$g = 0$;

Randomly initialize population sets of $\alpha_{ij}^{(0)}, \beta_{ij}^{(0)}, \gamma_{ij}^{(0)}$.

Evaluate $O_{ij}(\alpha_{ij}^{(0)}, \beta_{ij}^{(0)}, \gamma_{ij}^{(0)})$ for the whole initialized population.

while Termination criteria is not satisfied **do**

$g = g + 1$;

Apply **selection technique** from previous generation and assign it to $\{\alpha_{ij}^{(g)}, \beta_{ij}^{(g)}, \gamma_{ij}^{(g)}\}$

Apply **crossover** method on $\{\alpha_{ij}^{(g)}, \beta_{ij}^{(g)}, \gamma_{ij}^{(g)}\}$;

Apply **mutation** method on $\{\alpha_{ij}^{(g)}, \beta_{ij}^{(g)}, \gamma_{ij}^{(g)}\}$;

Apply **integer truncation** the current population, $\{\alpha_{ij}^{(g)}, \beta_{ij}^{(g)}, \gamma_{ij}^{(g)}\}$;

Evaluate $O_{ij}(\alpha_{ij}^{(g)}, \beta_{ij}^{(g)}, \gamma_{ij}^{(g)})$ for the whole current population;

end

Problem $\mathcal{P}'_1$ is subjected to all of the constraints in $\mathcal{P}_1$ with two additional constraints for the weighting variables. The sum of a_{0i} , a_{1i} , and a_{2i} is equal to 1 as shown in (5c) and (5d) defines that the values of a_{0i} , a_{1i} , and a_{2i} belong to $[0,1]$. It is expected that by solving $\mathcal{P}'_1$ has enhanced performance comparing to solving $\mathcal{P}_1$ and the suboptimal scheme.

There are different numerical techniques to solve mixed-integer problem, such as branch and bound. However, it is proven in [12] that genetic algorithm has a better performance comparing to other techniques [13]. Therefore, genetic algorithm is applied to solve the targeted problems. Algorithm 5 describes how the genetic algorithm technique is adopted.

Algorithm 5 begins by initializing the sets of optimization parameters $\{\alpha_{ij}, \beta_{ij}, \gamma_{ij}\}$ (i.e., population set). Then, the objective functions are evaluated using these population sets. In this work, a real-coded genetic algorithm (RCGA) approach is utilized. It is proposed in [13], in constructing the main elements of a genetic algorithm (i.e., crossover, mutation, and selection technique). RCGA uses real numbers for encoding and they have faster convergence rate than binary and gray coded genetic algorithms. The work in [13] is a pioneer work to combine a selection technique, a crossover operator, a mutation operator, and an integer truncation for solving mixed-integer problems. The selection technique that is adopted in the implemented algorithm is the tournament selection method, which is proposed by Goldberg and Deb [14].

The crossover operator used in this work is the Laplace crossover (LX) proposed in [15]. It is known that the density function of Laplace distribution is given by

$$f(x) = \frac{1}{2b} \exp\left(-\frac{|x-a|}{b}\right), \quad -\infty < x < \infty \quad (6)$$

where a is a location parameter, and b is the scaling parameter. In order to show how two offsprings $\mathbf{y}^{(1)} = \{y_i^{(1)}, \dots, y_i^{(1)}\}$ and $\mathbf{y}^{(2)} = \{y_i^{(2)}, \dots, y_i^{(2)}\}$ are generated from two parents

$\mathbf{x}^{(1)}$ and $\mathbf{x}^{(2)}$, several steps are followed. A uniformly distributed random variable $u \in [0, 1]$ is generated. Then, another random variable β that follows the Laplace distribution is generated by inverting the CDF of Laplace distribution as follows:

$$\beta_i = \begin{cases} a - b \log_2(u_i), & u_i \leq \frac{1}{2} \\ a + b \log_2(u_i), & u_i > \frac{1}{2} \end{cases} \quad (7)$$

Then, the offsprings are given as follows:

$$y_i^{(1)} = x_i^{(1)} + \beta_i \left| x_i^{(1)} - x_i^{(2)} \right| \quad (8)$$

$$y_i^{(2)} = x_i^{(2)} + \beta_i \left| x_i^{(1)} - x_i^{(2)} \right|. \quad (9)$$

For the mutation operation, power mutation (PM) scheme, which is proposed in [16], is utilized. The PM scheme utilizes the following power distribution:

$$f(x) = px^{p-1} \quad (10)$$

where p is the index of the distribution. To mutate the solution, a uniform random variable $t \in [0, 1]$ and a random variable that follows the distribution in (10) are generated. Then, the following formula is utilized to obtain the mutant solution:

$$y = \begin{cases} \bar{x} - s(\bar{x} - x^l), & \text{if } t < r \\ \bar{x} + s(x^u - \bar{x}), & \text{if } t \geq r \end{cases} \quad (11)$$

where $\bar{x}$ is the parent solution, $t = \frac{\bar{x} - x^l}{x^u - x^l}$, x^l and x^u are lower and upper bounds of the variable, and r is a variable between 0 and 1.

Finally, to satisfy the integer restrictions of the variables, a truncation procedure is adopted. If x_i is not integer, then the solution is $\bar{x}_i = [x_i]$ or $\bar{x}_i = [x_i] + 1$, each with probability 0.5, where $[\cdot]$ is the nearest integer approximation operation.

For solving $\mathcal{P}'_1$, the input parameters of Algorithm 5 include the weighting variables a_{0_i} , a_{1_i} , and a_{2_i} , in addition.

V. EVALUATION DATASET

In order to evaluate ADTVS, a real-life dataset is obtained from statistical data and actual geographical location. The details of this dataset are presented in this section. The work is focused in Saudi Arabia for two reasons. First, the proposed framework is more suitable for suburban and rural area. The residences have similar activity patterns and user preferences in these area. A BS has a higher chance to cover residences who have common interest on TV watching. The geographic location, where this study is applied, is a low-density living compound which is suitable for the proposed framework. Second, one of the mobile operators in Saudi Arabia, Mobily, has launched a new broadcasting service named as “mView” to deliver live TV and video on demand services recently since 2014 [17]. The company provides the service through various networks including fiber optic, 4G, 3G, and Wi-Fi. The amount of video traffic over the LTE network is expected to be increased significantly. It urges us to propose a smart resource allocation framework to prevent overloading the network in the future.

A. TV Audiences in Saudi Arabia

The surveys of TV audience behavior in Saudi Arabia are reported by Dubai Press Club and Pan Arab Research Center in 2007, 2011, and 2012. The data are extracted from these reports to construct a simulation dataset for validating the effectiveness of the proposed framework [18]–[20].

According to these reports, the average daily peak hours observed in afternoon are 13:00–14:30 and 16:00–17:00. The prime time period (i.e., the period with the most number of viewers in a day) is 20:00–00:00. The most watched TV channels are MBC 1, Al Arabiya, MBC 2, and Al Jazeera. In average, the viewers spend 2.7 h/day on watching TV [18]–[20]. For simplicity and without loss of generality, the seven most popular TV channels are selected for simulation. MBC 1 is a general family entertainment channel. MBC 2 is a movie channel. MBC 4 is tailored for Arab women. MBC Action is targeted for young Arab men. MBC Drama is a family channel, specially broadcasting drama series. Al Arabiya is a news channel. Al Jazeera is a news and current affairs channel.

B. Studied Geographic Location

King Abdullah University of Science and Technology (KAUST), located in Saudi Arabia, is considered as the study location. KAUST is a mid-size living compound with designed population of 20 000 people. The compound is well planned and well structured. Families and singles live in different districts in the compound separately. Professionals are mainly allocated in “Island” district. The residents of “Garden” district are mostly families and children. There are about 470 and 1500 town houses in these two districts, respectively. The “Harbor” district is mostly occupied by single graduate students in 80 apartment buildings. The locations of each house and building are shown in Fig. 4(a) and colored based on the regions. Furthermore, there are five operating BSs, shown as stars with the BS names in Fig. 4(a).

C. Assumptions and Parameters

The following assumptions are considered throughout the simulation. The daily average people using TV (PUT) level presented in [20] is adopted to estimate the overall number of audiences. The seven most popular TV channels are considered for simplicity. The audience sizes of the channels are approximated from [19]. Fig. 4(c) shows the average numbers of audiences for each TV channel in a day, grouped in 15 min.

It is assumed that there are 2 sets of watching equipment, such as TV sets, tablets, or smartphones, in each town house, and 20 sets of watching equipment in each apartment building, in a total of 5490 sets. The bitrates of the MBC channels, Al Arabiya, Al Jazeera are 700, 540, and 450kb/s, respectively. A static BS assignment is assumed for each house and building by selecting the strongest reception signal from the BS. Each BS has the same transmission power and coverage area. The receivers under the cell coverage have similar channel conditions to receive fair video quality. The assignment is colored in Fig. 4(b) according to the assigned BS. It is assumed that

Fig. 4. (a) Location of houses and buildings in three districts, grouped by “Island” (blue), “Harbor” (green), and “Garden” (purple). (b) BS assignment for each house and building grouped and colored by assigned BS. (c) Average daily numbers of audiences for TV channels, grouped by 15 min.

Fig. 5. Location of audiences at different time segments colored by the TV channels. (a) 07:00. (b) 21:00. (The color of each channel is the same as shown in Fig. 6.)

the audiences living in different districts have different user preferences. The majority of the “Island” audiences prefer news and cultural type channels, such as MBC 1 and Al Arabiya. The “Garden” audiences prefer families and leisure channels, such as MBC 4 and MBC Drama. Different ratings for each channel are applied to various districts for the diversity of TV channels selection. For the networking configuration, the parameters D and w are set to TDD mode and $10MHz$. It is based on the frequency spectrum arrangement for LTE operators in Saudi Arabia. The overhead parameter o is set to 0.1. The length of time segments is set to 15 min.

Two time segments 07:00 and 21:00 are chosen to show the sizes of audiences of TV channels and the location of users in the region in Figs. 5 and 6, respectively. These figures indicate that user preferences are varying in time and location. In the morning hours, more users watch Al Jazeera under the coverage area of BS 5914 and BS 5915. In the evening, significant diversities of user preferences are shown in different BSs. MBC 1, Al Arabiya, and MBC 4 are the most popular channels in BS 5915, BS 5914, and BS 5912, respectively. Because of the diversity in time and location, the static broadcast method which broadcasts all of the TV channels in the whole day and in all of the BSs is not efficient.

For the optimization process, genetic algorithm is applied to solve the optimization problems to find the corresponding optimal parameters. The ranges of α_{ij} , β_{ij} , and γ_{ij} are set to $\{4, 8, 16, 32\}$, $\{0-16\}$, and $\{0-20\}$, respectively. It is because, when the parameter S_{ij}^m is set to 4, α_{ij} is not allowed to be 1

Fig. 6. Numbers of audiences at BS stacked by TV channels. (a) 07:00. (b) 21:00.

or 2. Furthermore, since TDD mode is assumed, the maximum number of MBSFN subframes per allocation period is 20.

VI. EVALUATION RESULTS

In this section, the evaluation results are divided into four phases. First, the input parameters of each cell in the region are optimized independently by the ADTVS optimal scheme as shown in Problem $\mathcal{P}_1$. The cells at any time segment have their own sets of input parameters that are not related to other cells. Second, the input parameter β_{ij} is uniform for all of the cells in each time segment, such that, β_{ij} is equivalent to β_i . Thus, all cells have an identical modulation and coding rate scheme β_i that is able to form MBSFN. The purpose of having uniform β_{ij} is to evaluate the performances in cooperative broadcasting among BSs. In addition, the suboptimal scheme is evaluated in this part because β_{ij} for suboptimal scheme is uniformly set as well. In the above two cases, the weighting parameters a_0 , a_1 , and a_2 are set uniformly to $1/3$ for all time segments. Third, the differences of performances between cells are investigated to evaluate how user preferences in each cell affecting the performances. Finally, $\mathcal{P}'_1$ is solved and the set of variables, which includes weighting parameters for maximizing the associated objective function, is found.

A. Cells Independent Optimal

In this section, each cell is optimized independently, such that it has its own input parameters in each time segment.

Fig. 7. Result comparison of static broadcast and ADTVS cells independent optimal, average on cells. (a) Broadcast efficiency. (b) Percentage of conserved throughput. (c) Percentage of the served users. (d) Normalized optimized objective.

Fig. 7(a) shows the average broadcast efficiency of the ADTVS optimal scheme and the static broadcast method. In static broadcast, broadcast efficiency is directly proportional to the audience size in the whole region. The same amount of resources is consumed at anytime in all BSs. Broadcast efficiency increases with the number of audiences. In ADTVS optimal scheme, broadcast efficiency is higher because fewer TV channels are broadcast when the numbers of audiences are low. The gains of broadcast efficiency are significant in the morning and afternoon, reaching more than 200%. In the evening hours, the gains are less than 10%. The BSs broadcast fewer TV channels in the morning since the audience sizes are small. In the evening, more TV channels are broadcast due to the significant increases in audience sizes. Therefore, broadcast efficiencies of both methods are similar, such that the gains of broadcast efficiency are low from ADTVS optimal scheme in the evening.

From resource usage aspect, it requires 4.49Mb/s to broadcast all of the TV channels in each BS by the static broadcast method. By applying ADTVS optimal, more than 60% of the throughput is conserved in the morning. It saves 48% of the throughput in average comparing to the static broadcast method. Fig. 7(b) shows the percentage of conserved throughput in the region of a day. It is observed that more radio resources are conserved in the morning off-peak hours than the evening peak hours.

The ADTVS optimal scheme fulfill the constraint that at least 95% of users are served in each time segment at each BS. In average, 98.6% of users are served in the whole day as shown in Fig. 7(c). More users are satisfied in the evening hours since most of the channels are broadcast to fulfill the user preferences.

As shown in Fig. 7(d), the optimization objective of ADTVS optimal scheme is higher than the static broadcast, especially in the morning off-peak hours. This is mainly contributed by high broadcast efficiency and high percentage of conserved throughput.

B. Uniform β_{ij} for All Cells in Each Time Segment

In this section, the assignments of MCS index β_{ij} for BS are no longer independent. In order to form MBSFN, BSs are coordinated and assigned a uniform β_i to transmit identical signals for broadcasting TV channels. Furthermore, the performance of ADTVS suboptimal scheme is evaluated in this section. The β of ADTVS suboptimal is fixed to 16 and the parameter S^m is

Fig. 8. R_{ij}^a of ADTVS (a) suboptimal and (b) optimal schemes in uniform β_{ij} .

set to 4 in all time segments for all cells. Fig. 8(a) and (b) shows the corresponding R_{ij}^a from the parameter assignments of the suboptimal and optimal scheme, respectively. In the suboptimal scheme, maximum R_{ij}^a is reached in the peak hours (21:00–00:00). The cells consume a largest amount of available resources to broadcast in this period. By comparing these two figures, the suboptimal scheme shows a relatively steady assignment of R_{ij}^a , and the optimal scheme has a dynamic assignment. Since the audience size in BS 5918 is smaller than the other BSs, it has the lowest R_{ij}^a for broadcasting.

The evaluation results are shown in Fig. 9. In Fig. 9(a), the optimal scheme achieves the highest broadcast efficiency. In the peak hours, ADTVS suboptimal scheme has the same performance as static broadcast since all of the channels are broadcast in the region. In Fig. 9(b), both of the ADTVS suboptimal and optimal schemes conserve significant amount of throughput in the morning and afternoon. Although the performance of the optimal scheme is varying in Fig. 9(b) and (c), it balances the gains between three metrics to achieve the optimized objective as shown in Fig. 9(d). In the meanwhile, the result shows that ADTVS suboptimal scheme has close to optimal performance.

C. Intercell Performance Difference

In this section, the performances and the effects of user preferences between each cell are compared. Fig. 10(a)–(c) shows the number of watching audiences, broadcast efficiency, and conserved throughput of each cell, respectively. Since BS 5918 has the smallest audience size, it always has the lowest broadcast efficiency that fewest audiences are served per bit per second. There are two reasons that BS 5915 always achieves a higher broadcast efficiency than other BSs. First, observing

Fig. 9. Result comparison of static broadcast, ADTVS suboptimal, and optimal schemes in uniform β_{ij} , average on cells. (a) Broadcast efficiency. (b) Percentage of conserved throughput. (c) Percentage of the served users. (d) Normalized optimized objective.

TABLE II
SORTED CHANNELS SELECTION OF BS IN FOUR TIME SEGMENTS

	07:00	13:00	21:00	02:00
5915	Al Jazeera MBC 1 MBC Drama	MBC 1 Al Arabiya Al Jazeera	MBC 1 Al Arabiya Al Jazeera MBC 2 MBC 4 MBC Action MBC Drama	MBC 1 MBC 2 Al Jazeera MBC Drama
5913	MBC Drama Al Jazeera	Al Arabiya MBC 1 Al Jazeera	MBC 4 Al Arabiya MBC 1 Al Jazeera MBC Drama	MBC 1 MBC 4 MBC 2 MBC Drama

from Fig. 10(a), BS 5915 has higher numbers of audiences than other BSs. Second, BS 5915 has a lower diversity in user preferences for choosing TV channels. For example, in Fig. 6(b), more than half of the audiences watch MBC 1 in BS 5915. MBC 1 dominates the TV penetration in this cell and contributes to a high broadcast efficiency. The BS consumes only 700kb/s throughput to serve about 320 users at 21:00. On the other hand, BS 5913 has a higher diversity of user preferences that the audience sizes of each channel are close to each other. For example, in Fig. 6(b), the first three popular channels (i.e., MBC 4, Al Arabiya, and MBC 1) in BS 5913 have similar numbers of audiences. This requires about 2Mb/s throughput to broadcast these three channels but serving only 250 audiences. Therefore, it has a lower broadcast efficiency. Table II shows the TV channels that are broadcast in these two BSs. The channels are sorted by the TV popularity in descending order. Although they have similar numbers of channel selection, BS 5915 serves more number of audiences so it achieves the highest broadcast efficiency in the region. Furthermore, by comparing the performances in Fig. 10(c), the cells do not have big differences in terms of conserving radio resources. This means that the cells consume similar amount of resources for broadcasting, but some of the cells serve more audiences to achieve higher broadcast efficiency. In summary, a lower diversity of user preferences and a larger audience size lead to a higher broadcast efficiency.

D. Optimized Weighting Variables

In the objective function, the weights decide the importance of the three metrics, a_0 for broadcast efficiency, a_1 for conserved throughput, and a_2 for the number of served users. In the previous sections, the weighting parameters are uniformly assigned, such that the three metrics have the same importance to the overall objective. In this section, $\mathcal{P}'_1$ is solved to find

the optimized weighting variables and the values are shown in Fig. 11(a). In the morning hours, a_{1_i} dominates other weights. It indicates that conserving throughput achieves the highest overall objective. It is because the audience size in the morning is small comparing to afternoon and evening. Broadcasting in the morning hours is inefficient and conserving radio resources is a better choice. In the afternoon peak hours (13:00–14:30), since the audience size increases, the weights of broadcast efficiency and served users increase to achieve a higher objective. In the evening peak hours (20:00–00:00), serving users has the top priority, thus the highest weight is given. In Fig. 11(b) and (c), comparisons with previous cases are shown. Optimizing weighting variables has a wider range of variation. The variation is caused by the rapid change of the values of weights. However, multiplying the weights and the metrics gives the best overall objective among the other cases as shown in Fig. 11(d). On the other hand, the overall performances of the previous two cases are similar. They show the highest broadcast efficiency but lowest percentage of served users in the afternoon peak hours. In the evening peak hours, all methods have similar performance as the static broadcast. In summary, dynamic resources' allocation in ADTVS achieves higher broadcast efficiency and conserves more radio resources in the off-peak hours while preserving similar performances as static broadcast in the peak hours. ADTVS always outperforms the static broadcast method.

VII. DISCUSSION

ADTVS does address many current issues but is not without issues of its own. Although it does not serve all audiences, unserved audiences could be advised to watch TV channels through unicast connection or alternative networks, such as WiFi and 3G. Cooperative scheduling with unicast and/or other networks helps to serve all of the audiences with minimum amount of resources. The valuable 4G radio resources should be better utilized on providing high broadcast efficiency services that serve larger number of users rather than broadcasting unpopular TV channels. Moreover, commercial operators are now enthusiastic about building WiFi networks in shopping malls, traffic stations, and crowded areas to offload the mobile network traffic onto WiFi networks. The calls and data traffic could be seamlessly redirected between the different kinds of networks. Users are only required to pay a fixed fee to use the

Fig. 10. Cells performance comparison. (a) Number of watching audiences of each cell. (b) Broadcast efficiency of each cell. (c) Conserved throughput of each cell.

Fig. 11. (a) Value of optimized weighting variables and comparison result of all cases. (b) Average broadcast efficiency of all cases. (c) Average percentage of served users of all cases. (d) Objective comparison of all cases. Inde, cells independent optimal; uniform beta, uniform β_{ij} for all cells in each time segment; Opt-w, optimized weighting variables; static, static broadcast.

service and therefore are not forced to pay more, while their TV channels are not broadcast by the network.

In the future, ADTVS could be extended by upgrading algorithms with physical and/or link layer techniques, as well as audience behavior prediction to achieve better performance. The modular design of ADTVS separates the framework into various algorithms. Each algorithm can be upgraded and adjusted independently without affecting the other modules. In Algorithm 2, the available resources are estimated from the BS point of view without consideration of reception ability of receivers in the cell to determine a suitable physical layer MCS. Receivers' signal-to-noise ratio (SNR) is one of the important factors that should be considered for assigning appropriate MCS. In the future, physical and/or link layer techniques can be considered to add in the algorithm to increase the accuracy on the estimation. Superposition coded multicasting (SCM) is one of the physical layer techniques that has been proved to solve the multiuser diversity problem [21]. It suggests suitable MCSs for broadcasting video in a cell, by considering both good and bad wireless channel conditions of all of the receivers. In Algorithm 3, a simple and straight forward metric (i.e., historical audience statistic) is applied to measure the popularity of TV channels. The popularity of TV channels implicitly affects broadcast efficiency, which eventually affects the optimization decision. Detailed research is conducted on investigating the relationship between popularity of TV channels and broadcast efficiency in [22]. In the future, several ideas can be implemented into this algorithm for extension. First, video quality prediction over 4G network is introduced

in [23]. Video encoding and network configuration parameters are evaluated by data mining methods to investigate the correlation between these parameters and the video quality in 4G networks. The prediction could help to measure the quality-of-experience (QoE) in this algorithm to provide a higher accuracy of the popularity. Second, Luo *et al.* proposed a data mining model to analyze viewing behaviors of audiences in Internet protocol TV (IPTV) systems [24]. This method provides a reliable estimation in the algorithm to measure the popularity of TV channels according to audience preferences. Third, social network and social behavior could be applied for TV channels popularity prediction [25]–[27]. Fourth, Kryftis *et al.* propose two algorithms for optimal selection of multimedia content to balance delivery load [28]. Their prediction engine predicts the future loading on the network and optimize the QoE for the end users.

VIII. CONCLUSION

In conclusion, Addressing the needs of the charging sphere of broadcast transmissions is done by a system-level scheduling framework. ADTVS takes audience preferences into account in the process of allocating radio resources in TV broadcasting services over 4G LTE networks. The framework consists of three algorithms: one for resource estimation, one for TV channels popularity measurement, and the last for resource allocation. Furthermore, two schemes are introduced for dynamic assignment of input parameters of ADTVS. A simulation is conducted by considering Saudi Arabia as a case study and

compared the proposed framework with the static broadcast method. The framework is designed for both suburban and rural areas and easily transplant in other locations and countries. The evaluation results show that ADTVS achieves a higher broadcast efficiency and conserved significant amount of radio resources with only limited number of unserved users as tradeoff.

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