Spectral Efficiency Performance of MBSFN-enabled LTE Networks

Antonios Alexiou[2], Christos Bouras[1,2], Vasileios Kokkinos[1,2], Andreas Papazois[1,2], George Tsichritzis[1,2]
[1] Research Academic Computer Technology Institute
[2] Computer Engineering and Informatics Department, University of Patras
Patras, Greece
alexiua@ceid.upatras.gr, bouras@cti.gr, kokkinos@cti.gr, papazois@ceid.upatras.gr, tsixritzis@cti.gr

***Abstract*—Long Term Evolution (LTE) constitutes the latest step before the 4th generation (4G) of radio technologies designed to increase the capacity and speed of mobile communications. To support Multimedia Broadcast/Multicast Services (MBMS), LTE offers the possibility to transmit Multimedia Broadcast multicast service over a Single Frequency Network (MBSFN), where a time-synchronized common waveform is transmitted from multiple cells for a given duration. This enables over-the-air combining, thus improving the Signal to Interference plus Noise Ratio (SINR) and spectral efficiency (SE) significantly compared to conventional MBMS operation. In this paper, we analytically calculate the SE performance achieved in a MBSFN area for a dynamically changing user topology and different modulation and coding schemes (MCS). Finally, based on the SE measurement, we determine the MCS scheme that either maximizes or achieves a target SE for the corresponding user distribution.**

Keywords-Multimedia Broadcast/Multicast Services, Long Term Evolution; Single Frequency Network, Spectral efficiency

I. INTRODUCTION

The Long Term Evolution (LTE) project is focused on enhancing the Universal Terrestrial Radio Access (UTRA) and optimizing 3rd Generation Partnership Project's (3GPP) radio access architecture. LTE supports scalable carrier bandwidths and provides downlink peak rates of at least 100 Mbps, an uplink of at least 50Mbps and round-trip times of less than 10ms. Orthogonal Frequency Division Multiplexing (OFDM) has been selected for the downlink and Single Carrier-Frequency Division Multiple Access (SC-FDMA) for the uplink.

Moreover, 3GPP has introduced the Multimedia Broadcast/Multicast Service (MBMS) as a means to broadcast and multicast information to 3G and 4G users. MBMS is an efficient method for delivering multimedia content to multiple destinations by allowing resources to be shared in an economical way [1], [2].

In the context of the Long Term Evolution of 3G systems, the MBMS will evolve into the e-MBMS ("e-" stands for evolved). The LTE e-MBMS aims at providing broadcast and multicast services, combining flexibility and high efficiency in the spectrum occupancy. This will be achieved through increased performance of the air interface that will include a new transmission scheme called Multimedia Broadcast multicast service over a Single Frequency Network (MBSFN). In MBSFN operation, MBMS data are transmitted simultaneously over the air from multiple tightly time-synchronized cells. A group of those cells which are targeted to receive these data constitute the so-called MBSFN area [3].

The MBSFN transmission mode leads to significant improvements in spectral efficiency (SE) compared to Universal Mobile Telecommunications System (UMTS) MBMS, since the MBSFN transmission greatly enhances the Signal to Interference Noise Ratio (SINR). This is extremely beneficial at the cell edge, where transmissions (which in UMTS are considered as inter-cell interference) are translated into useful signal energy and hence the received signal strength is increased; while, at the same time the interference power is largely reduced [4]. In general, MBSFN offers better performance compared to classic single cell point-to-point (PTP) or point-to-multipoint (PTM) transmissions [5], [6].

In this paper, we evaluate the performance of MBSFN in terms of SE. Several studies such as [7], [8] and [9] have shown that SE is directly related to the modulation and coding scheme (MCS) selected for the transmission. Additionally, the most suitable MCS is selected according to the measured SINR so as a certain Block Error Rate (BLER) target is achieved. Taking into account the above, we focus on a dynamic user distribution, with users distributed randomly in the MBSFN area and therefore experiencing different SINRs. Based on the measured SINRs, our goal is to select the MCS which should be used by the base stations when transmitting the MBMS data. For this purpose, we consider the following three different approaches with different goals set in each one of them:

- The 1st approach selects the MCS that ensures that even the users with the lowest SINR receive the MBSFN service. We show that a disadvantage of this approach is that users may experience a low SE (Bottom up approach).
- The 2nd approach selects the MCS that ensures the maximum SE over all the users in the topology (Top down approach).
- The 3rd approach selects the MCS that achieves a target SE (Predefined setting approach).

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The paper is structured as follows: in Section II we present an overview of MBSFN architecture. The SE evaluation of the MBSFN delivery scheme is described in Section III. In Section IV, we present in detail the three different approaches for selecting the MCS; while the evaluation results are presented in Section V. Finally, the conclusions and planned next steps are briefly described in Section VI.

II. e-MBMS LTE Architecture

The e-MBMS architecture is illustrated in Figure 1. Within evolved UTRA Network (e-UTRAN), the e-NBs (evolved Node B or base station) are the collectors of the information that has to be transmitted to users over the air-interface. The Multi-cell/multicast Coordination Entity (MCE) is coordinating the transmission of synchronized signals from different cells (e-NBs). MCE is responsible for the allocation of the same radio resources, used by all e-NBs in the MBSFN area for multi-cell MBMS transmissions. Besides allocation of the time/ frequency radio resources, MCE is also responsible for the radio configuration e.g. the selection of the MCS. The e-MBMS Gateway (e-MBMS GW) is physically located between the evolved Broadcast Multicast Service Center (e-BM-SC) and e-NBs and its principal functionality is to forward the MBMS packets to each e-NB transmitting the service. Furthermore, e-MBMS GW performs MBMS Session Control Signaling (Session start/stop) towards the e-UTRAN via the Mobility Management Entity (MME). The e-MBMS GW is logically split into two domains. The first one is related to control plane, while the other one is related to user plane. Likewise, two distinct interfaces have been defined between e-MBMS GW and e-UTRAN, namely M1 for user plane and M3 for control plane. M1 interface makes use of IP multicast protocol for the delivery of packets to e-NBs. M3 interface supports the MBMS session control signaling, e.g. for session initiation and termination [3], [4].

The e-BM-SC is the entity in charge of introducing multimedia content into the 4G network. For this purpose, the e-BM-SC serves as an entry point for content providers or any other broadcast/multicast source which is external to the network.

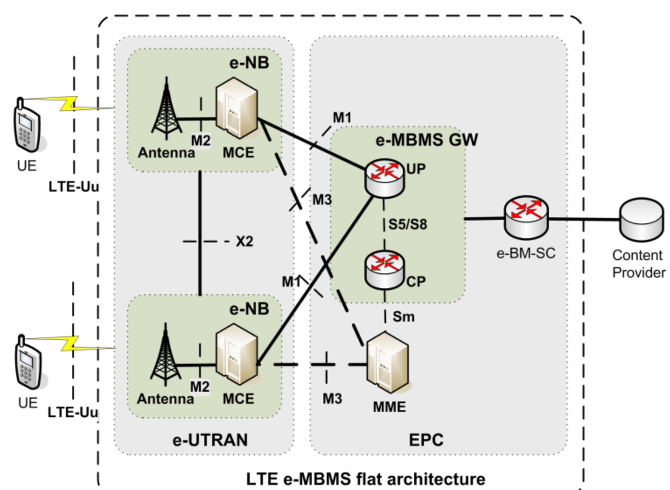

Figure 1. e-MBMS flat architecture.

In MBSFN, the transmission takes place from a time-synchronized set of e-NBs using the same resource block. The OFDM symbols in MBSFN contain a cyclic prefix (CP), which however is slightly longer than the CP used in conventional transmissions. This fact enables the User Equipment (UE) to combine transmissions from different e-NBs located far away from each other [5].

III. Spectral Efficiency Evaluation

In order to calculate the SE in the case of a single receiver, the following procedure that consists of four distinct steps is used.

A. Step 1: SINR Calculation

Let the MBSFN area consist of N neighboring cells. Due to multipath, the signals of the cells arrive to the receiver by M different paths, so the average SINR at a given point m is expressed as in (1) [7]:

$$SINR(m) = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\frac{w\left(\tau_i(m)+\delta_j\right)P_j}{q_i(m)}}{\sum_{i=1}^{N}\sum_{j=1}^{M}\frac{\left(1-w\left(\tau_i(m)+\delta_j\right)\right)P_j}{q_i(m)}+N_0} \quad (1)$$

with:

$$w(\tau) = \begin{cases} 1 & 0 \le \tau < T_{CP} \\ 1-\frac{\tau - T_{CP}}{T_u} & T_{CP} \le \tau < T_{CP}+T_u \\ 0 & otherwise \end{cases} \quad (2)$$

where P_j is the average power associated with the j path, $\tau_i(m)$ the propagation delay from base station i, δ_j the additional delay added by path j, $q_i(m)$ the path loss from base station i, T_{cp} the length of the cyclic prefix and T_u the length of the useful signal frame.

SINR is usually calculated in Orthogonal Frequency Division Multiple Access (OFDMA) for each subcarrier and all the SINRs are combined in order to find a non-linear average SINR (effective SINR or γ_{eff}), using the Exponential Effective SIR Mapping (EESM) [10].

$$\gamma_{eff} = EESM(\gamma_i,\beta) = -\beta\cdot\ln\left(\frac{1}{N}\cdot\sum_{i=1}^{N}e^{-\frac{SINR_i}{\beta}}\right) \quad (3)$$

where N is the number of subcarriers and β is calibrated by means of link level simulations to fit the compression function to the Additive White Gaussian Noise (AWGN) [10].

However, in 3GPP LTE systems, adjacent subcarriers allocation is considered, making subcarriers allocated to one TV channel experiencing similar fading conditions. All subcarriers allocated to a given TV channel will thus experience the same fast fading and their SINR will be equal (γ_{eff} = SINR) [7].

B. Step 2: Channel Quality Indicators (CQI) Mapping

In order to obtain the BLER for a given MCS, AWGN simulations have been performed. The MCS determines both the modulation alphabet and the Effective Code Rate (ECR) of the channel encoder. Figure 2 shows the BLER results of Channel Quality Indicators (CQI) 1-15 without using Hybrid Automatic Repeat Request (HARQ), for 1.4 MHz and 5.0 MHz bandwidth. The results have been obtained from the link level simulator introduced in [10]. Each MCS is mapped to a predefined CQI value. The 15 different sets of CQIs and the corresponding MCSs are defined in [11].

In LTE networks, an acceptable BLER target value should be smaller than 10% [10]. The SINR to CQI mapping required to achieve this goal can thus be obtained by plotting the 10% BLER values over SNR of the curves in Figure 2. The 10% BLER values for each CQI are depicted in Figure 3. Using the obtained line, the γ_{eff} can be mapped to a CQI value that should be signaled to the e-NB so as to ensure the 10% BLER target.

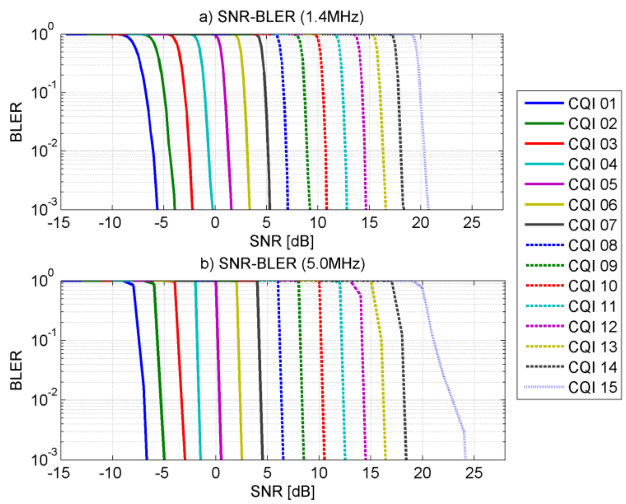

Figure 2. SNR-BLER curves obtained for: a) 1.4 MHz, b) 5.0 MHz.

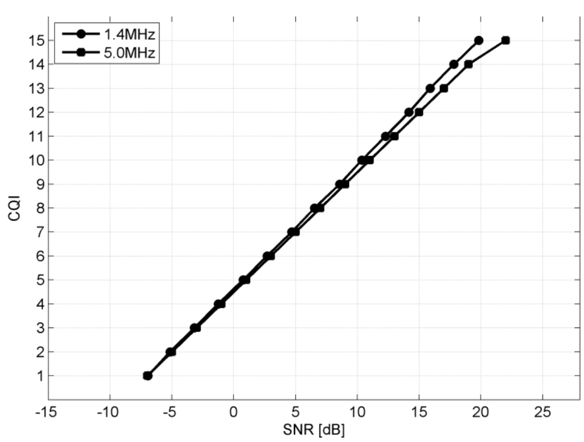

Figure 3. SINR to CQI mapping.

C. Step 3: Throughput Estimation

The achieved throughput is calculated as in (4), where *BW* is the total bandwidth offered by LTE, *e(SINR)* is the effective code rate of the selected modulation scheme and *BLER(SINR)* the block error rate [12].

$$Throughput = BW \cdot e(SINR) \cdot (1 - BLER(SINR)) \tag{4}$$

Therefore, by utilizing the SINR and CQI obtained by the CQI mapping step, the achieved throughput may be calculated. Figure 4a and Figure 4b depict the relationship between the achieved throughput and the SNR for all MCSs in the case of 1.4 MHz and 5.0 MHz respectively.

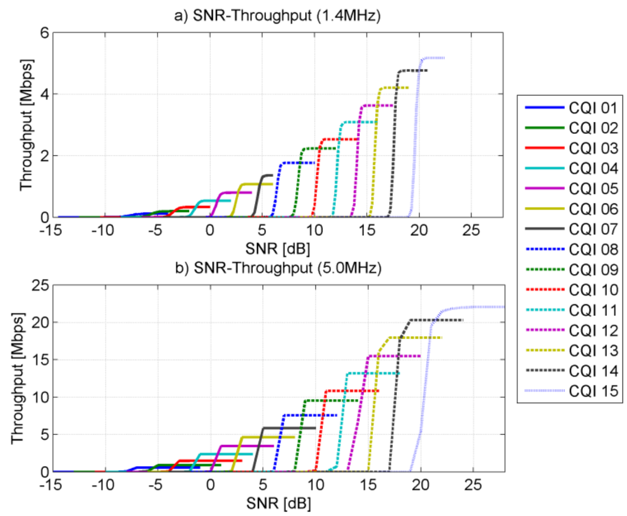

Figure 4. Throughput for all CQIs obtained for: a) 1.4 MHz, b) 5.0 MHz.

D. Step 4: Single User Spectral Efficiency

Spectral efficiency (SE) refers to the information rate that can be transmitted over a given bandwidth in a specific communication system. It constitutes a measure of how efficiently a limited frequency spectrum is utilized. The formula from which the SE can be obtained is:

$$SE = \frac{Throughput}{BW} \tag{5}$$

To sum up, for a single user γ_{eff} is calculated from (1), (2) and (3); while the achieved SE may be obtained from (4) and (5). If, for example, the effective SINR for a random user in the topology is 5dB and the bandwidth 5.0 MHz, from Figure 3 we obtain the equivalent CQI (CQI = 7). For the specific CQI and SINR value, the throughput as obtained from Figure 4 is 6 Mbps. Therefore, the SE as calculated from (5) is 1.2 (bit/s)/Hz.

IV. MBSFN Area Spectral Efficiency

The SE in the "multiple users" case is deduced from the single user approach, described in the previous section. In the case of multiple users, the value of the total SE depends on the MCS selected for the MBSFN transmission. In this section we examine three different approaches for the selection of the MCS.

A. 1st Approach - Bottom Up Approach

The 1st approach ensures that all users, even those with the lowest SINR, will receive the MBSFN service. In order to achieve this goal the algorithm finds the minimum SINR and the MCS that corresponds to the minimum SINR is obtained from the SINR to CQI mapping (Figure 3). Then, from (4) or Figure 4 the corresponding average throughput and SE are obtained. The operation of this approach indicates that all the users in the MBSFN area will uninterruptedly receive the MBMS service, irrespectively of the conditions they experience (in terms of SINR). However, the main disadvantage of this approach is that users with SINRs greater than the minimum SINR are not making use of a MCS that would ensure a greater throughput. The procedure for obtaining the MCS and the SE is presented using pseudo code in the following table.

```
Define MBSFN topology
for i = 1:total_users
    Calculate SINR(i)
end
%find the lowest SINR
min_SINR = min(SINR)
%choose the MCS that corresponds to the min SINR from
%SINR to CQI mapping
selected_MCS = f_MCS (min_SINR)
%Calculate the throughput for the selected MCS
throughput = f_throughput(selected_MCS, min_SINR)
Calculate SE
```

B. 2nd Approach - Top Down Approach

The 2nd approach selects the MCS that ensures the maximum average throughput over all users in the MBSFN area. At first the algorithm calculates the SINR value for each user using (1). Then, the algorithm scans all the MCSs (Figure 4). For each MCS, the algorithm calculates the per-user throughput depending on the calculated SINRs and obtains the average throughput and total SE. The MCS that ensures the maximum average throughput - and therefore the maximum total SE - is selected. The following table presents the procedure for obtaining the MCS and the SE according to the 2nd approach using pseudo code.

```
Define MBSFN topology
for i = 1:total_users
    Calculate SINR(i)
end
% for each modulation and coding scheme
% calculate the average throughput over all users
for MCS = 1:15
    for j = 1:total_users
        throughput(MCS, j) = f_throughput (MCS, SINR(j))
    end
    avg_throughput(MCS) = average(throughput(MCS, :))
    % calculate the corresponding spectral efficiency
    Calculate SE(MCS)
end
%find the max spectral efficiency that can be achieved
SE = max(SE(:))
```

C. 3rd Approach - Predefined Setting Approach

The goal of the 3rd approach is to find the MCS in order for a target SE (usually equal to 1 (bit/s)/Hz) to be achieved [7]. The operation of this approach is similar to the operation of the 2nd approach. Initially the algorithm calculates the SINR value for each user. However, contrary to the 2nd approach, the algorithm does not necessarily scan all the MCSs of Figure 4. Starting from the lowest MCS, the algorithm calculates the per-user throughput and obtains the average throughput and total SE of each MCS. If during the scan one MCS ensures that the total SE is equal or higher than the target SE, the operation stops and the algorithm selects this MCS for the delivery of the MBMS data. In other words, the aim of this approach is to find the lowest MCS that allows a target SE to be achieved. In the case the target SE cannot be achieved, this approach has identical operation with the 2nd approach (i.e. selects the MCS that ensures the maximum total SE). This procedure is presented using pseudo code in the following table.

```
Define MBSFN topology
Define target_SE
for i = 1:total_users
    Calculate SINR(i)
end
% for each modulation and coding scheme
% calculate the average throughput over all users
for MCS = 1:15
    for j = 1:total_users
        throughput(MCS, j) = f_throughput (MCS, SINR(j))
    end
    avg_throughput(MCS) = average(throughput(MCS, :))
    % calculate the corresponding spectral efficiency
    Calculate SE(MCS)
    % examine if target SE is achieved
    if SE(MCS) >= target_SE      % target is achieved
        break;
    else      % target is not achieved
        SE = max(SE(:))
    end
end
SE = SE(MCS)
```

V. PERFORMANCE EVALUATION

This section provides the simulation results of the SE performance evaluation of MBSFN using the analytical model presented in the previous paragraphs. Two different scenarios are investigated. Scenario 1 assumes that 50 users are randomly distributed in the MBSFN area; while Scenario 2 investigates the case of variable number of users. The parameters used in the performed simulations are presented in the following table.

TABLE I. SIMULATION SETTINGS

Parameter	Value
Cellular layout	Hexagonal grid, 19 cell sites
Inter Site Distance (ISD)	1732 m
Carrier frequency	2.0 GHz
System bandwidth	1.4 MHz / 5.0 MHz
Channel model	3GPP Typical Urban
Propagation model	Cost Hata
Cyclic prefix length	16.67μsec
Useful signal frame length	66.67μsec
Modulation and Coding Schemes	15 different sets defined in [11]

A. *Scenario 1: Constant Number of Users*

This paragraph examines the operation of the three approaches for constant number of users in the MBSFN area. More specifically, the MBSFN area - which consists of four neighboring cells - contains 50 randomly distributed users.

For the evaluation of the 1st approach, we first consider the case of 1.4 MHz bandwidth. According to the procedure described in paragraph IV.A, initially the users' SINRs are obtained and the lowest SINR value is selected for the determination of the MCS. In the examined scenario, the lowest SINR is -1.845dB. Therefore, from Figure 3 the MCS corresponding to CQI 3 is selected. Indeed, Figure 5a confirms that CQI 3 may provide the maximum achieved throughput (0.326 bit/s) for this specific value of SINR. The equivalent SE as calculated from (5) is 0.233 (bit/s)/Hz. The examination of Figure 5b leads to similar results. In this case, CQI 3 is also selected, however the maximum throughput is 1.470 bit/s and the total SE 0.294 (bit/s)/Hz. However, it is worth mentioning that all the users in the MBSFN area will receive the MBMS service with the corresponding throughput, irrespectively of the conditions they experience in terms of SINR.

The SE for all CQIs as calculated with the 2nd approach is depicted in Figure 6a and Figure 6b for 1.4 MHz and 5.0 MHz bandwidth respectively. More specifically, both figures present the total SE per CQI after the scanning procedure. In both cases the selected CQI after the scanning procedure is CQI 13, since it may achieve the highest value of total SE. From Figure 6a we may notice that for 1.4 MHz bandwidth and for the specific user distribution, the achieved SE is 1.504 (bit/s)/Hz. On the other hand for 5.0 MHz bandwidth the achieved SE is 1.794 (bit/s)/Hz (Figure 6b).

Finally, regarding the 3rd approach (Figure 7), the algorithm scans the MCSs beginning from the MCS that corresponds to CQI 1. For each MCS the average throughput and total SE are calculated. However, contrary to the 2nd approach, the scanning operation stops when the total SE reaches the target SE, which equals to 1 (bit/s)/Hz. As depicted in Figure 7a for 1.4 MHz bandwidth the first CQI that achieves the SE target (1 (bit/s)/Hz) and therefore is selected for the transmission of the MBMS data, is CQI 9. On the other hand, for the case of 5.0 MHz bandwidth, CQI 8 is selected.

To sum up, the selected MCS and the achieved SE of each approach for the specific user distribution are depicted in Figure 8a and Figure 8b, for 1.4 MHz and 5.0 MHz bandwidth respectively. As expected, the 2nd approach is capable of achieving the maximum SE.

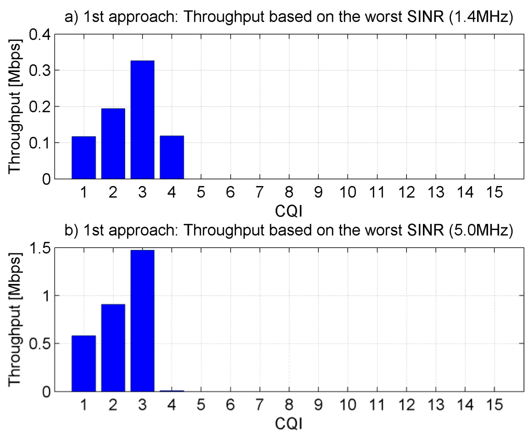

Figure 5. Throughput for all CQIs based on the user with the lowest SINR value (1st approach) for: a) 1.4 MHz, b) 5.0 MHz.

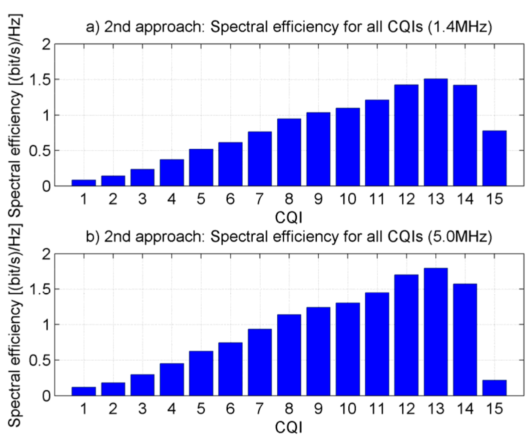

Figure 6. Spectral efficiency for all CQIs (2nd approach) for: a) 1.4 MHz, b) 5.0 MHz.

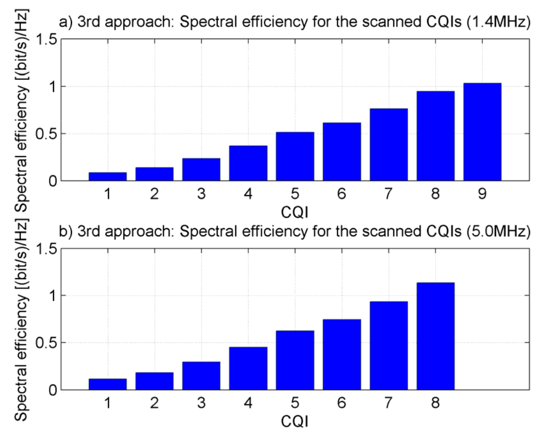

Figure 7. Spectral efficiency only for the CQIs scanned in order to reach the SE target (3rd approach) for: a) 1.4 MHz, b) 5.0 MHz.

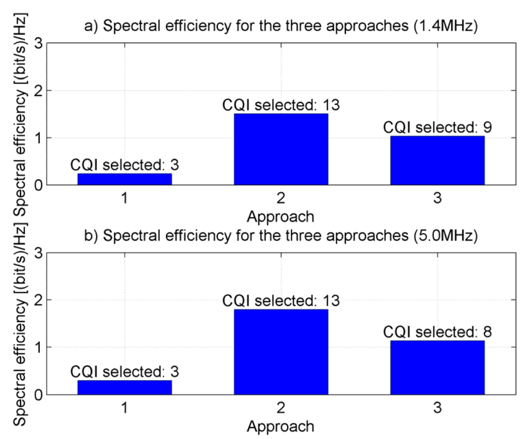

Figure 8. Achieved spectral efficiency and selected CQI for each approach and: a) 1.4 MHz, b) 5.0 MHz.

B. *Scenario 2: Variable Number of Users*

In this paragraph we present simulation results concerning the operation of the proposed approaches for variable number of UEs. More specifically, Figure 9 and Figure 10 examine the performance of each approach in terms of SE and selected MCS, when the users' population in the MBSFN area varies from 1 to 1000 users (for 1.4MHz and 5.0MHz bandwidth respectively). All the users that receive the MBMS service appear in random initial positions throughout the MBSFN area, which consists of four neighboring and tightly time-synchronized cells. The remaining simulation parameters of the corresponding scenario are in accordance with Table I.

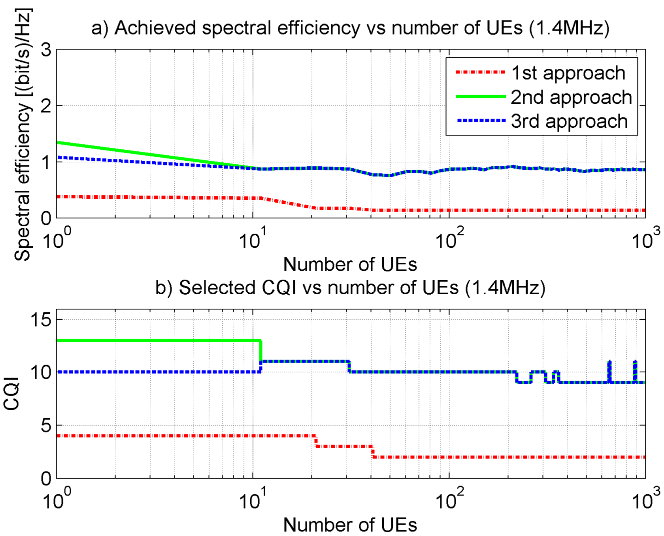

Figure 9. Achieved spectral efficiency and selected CQI for variable number of users (1.4 MHz).

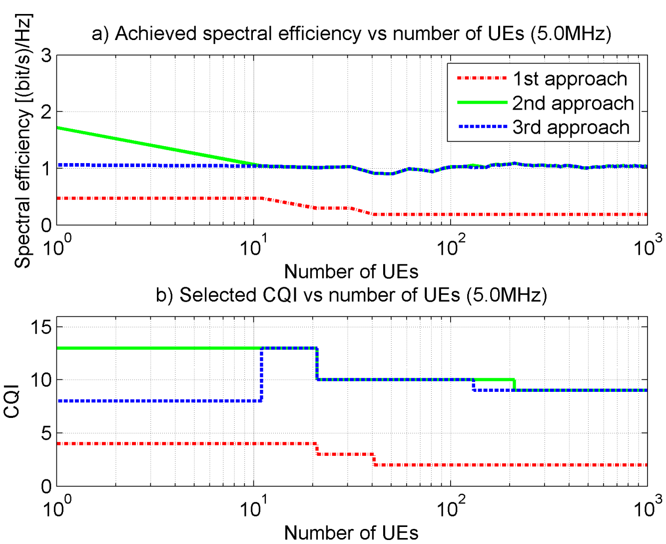

Figure 10. Achieved spectral efficiency and selected CQI for variable number of users (5.0 MHz).

Figure 9a and Figure 10a are indicative examples of the operation of each approach even though the users' distribution in the MBSFN area is random. In both cases, the 1st approach (Bottom up approach) achieves the lowest SE for the corresponding user population. On the other hand, the fact that this approach takes into account the lowest SINR in order to obtain the corresponding MCS, ensures that even the users that experience bad conditions (e.g. users in the borders of the MBSFN area) will receive the MBMS service. As consequence, the users with better conditions will not receive the service with the highest possible throughput.

The 2nd approach (Top down approach) has the best performance in terms of SE, especially for small number of users. Indeed, as expected, the 2nd approach ensures the maximum average throughput irrespectively of the UE population in the topology and as an aftermath achieves the maximum SE. It is also worth mentioning that in certain scenarios where the users are not very scattered in the topology, the 2nd approach could achieve even higher values of SE. On the other hand, in order to achieve such high values of SE compared to the other two approaches, the 2nd approach utilizes higher modulation schemes (Figure 9b and Figure 10b). Therefore, many users that experience bad conditions do not receive the MBMS service at all.

Finally, from Figure 9 and Figure 10 it is obvious that the 3rd approach (Predefined setting approach) selects the MCS that satisfies the SE target. Therefore, in Figure 9 (1.4 MHz bandwidth) for less than ten UEs, the 3rd approach utilizes CQI 10 in order to deliver the MBMS service, while in Figure 10 (5.0 MHz bandwidth) the selected CQI is CQI 8. As depicted in Figure 9 and Figure 10, the specific modulation schemes may achieve a SE value higher than the SE target. In the cases when the SE target is not satisfied (e.g. in Figure 9 for UE population larger than ten and in Figure 10 larger than twenty users), this approach has identical performance with the 2nd approach. Therefore, it utilizes the modulation scheme that ensures the highest SE.

TABLE II. APPROACHES COMPARISON

Approach	Throughput	Spectral efficiency	Service Provision
1st	Minimum	Minimum	Guaranteed
2nd	Maximum	Maximum	Not Guaranteed
3rd	Medium	Target	Not Guaranteed

To sum up, Table II presents a cumulative, direct comparison between the approaches analyzed in this paper. The main conclusion is that the selection of the most efficient MCS is an operator dependent parameter. Therefore, the uninterrupted service provision irrespectively of the users' conditions would make the 1st approach the most efficient approach. However, this approach could not provide any guarantee for the throughput and the achieved SE. On the other hand, for maximum average throughput and maximum SE the most efficient approach would be the 2nd approach. Finally, the 3rd approach constitutes the most efficient approach when the operator targets at a specific SE value.

VI. Conclusions and Future Work

In this paper, a performance evaluation of an MBSFN enabled LTE network is presented in terms of spectral efficiency. The evaluation methodology is based on the selection of the appropriate MCS for a specific MBSFN session that achieves an acceptable spectral efficiency. Three different approaches are considered for the determination of the acceptable spectral efficiency. The 1st approach selects the MCS that ensures that even the users with the lowest SINR will receive the MBSFN service. The 2nd approach selects the MCS that ensures the maximum SE while the 3rd approach selects the MCS that achieves a predefined target SE. The performance evaluation that we present considers different scenarios of user population and examines two different carrier bandwidths (1.4 and 5.0 MHz). We have shown that all the approaches are capable of selecting the most efficient MCS in order to fulfill the operator's planning and scheduling and the users' needs.

The step that follows this work could be the design and the evaluation of an algorithm responsible for selecting the most efficient of the above three approaches according to operator needs each time. In parallel, our main goal is to propose novel methods for improving the performance of the MBSFN transmission, in terms of spectral efficiency. Based on the fact that the MBSFN performance depends on the cells' deployment (e.g. when apart from the cells that contain users, neighboring cells assist in the MBSFN transmission as well) our goal is to examine an algorithm responsible for selecting the most efficient MBSFN deployment scheme for the transmission of the multimedia data.

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