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Modulation and coding scheme selection in multimedia broadcast over a single frequency network-enabled long-term evolution networks

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SUMMARY

Long term evolution constitutes the next generation cellular network beyond 3G that is designed to support the explosion in demand for bandwidth-hungry multimedia services in wireless networks by providing an extremely high performance radio access technology. To support multimedia broadcast/multicast services (MBMS), long term evolution offers the functionality to transmit MBMS over a single frequency network, where a time-synchronized common waveform is transmitted from multiple cells for a given duration. This enables over-the-air combining, thus significantly improving the spectral efficiency (SE) compared with conventional MBMS operations. In MBMS over a single frequency network transmissions, the achieved SE is mainly determined by the modulation and coding scheme selected. This study proposes and evaluates four approaches for the selection of the modulation and coding scheme. Each approach corresponds to different users' distribution and multimedia traffic conditions. On the basis of SE measurements, we determine the approach that either maximizes or achieves a target SE for the corresponding users' distribution and traffic conditions. Copyright © 2011 John Wiley & Sons, Ltd.

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KEY WORDS: long term evolution; modulation and coding scheme; multimedia broadcast and multicast; single frequency network; spectral efficiency

1. INTRODUCTION

Long term evolution (LTE) constitutes the evolution of the third-generation mobile telecommunications technologies. LTE utilizes orthogonal frequency division multiple access to enhance the 3rd Generation Partnership Project's (3GPP) radio interface. This radio technology is optimized to enhance networks by enabling new high capacity mobile broadband applications and services, while providing cost-efficient ubiquitous mobile coverage [1].

3GPP introduced the multimedia broadcast/multicast service (MBMS) as a means to broadcast and multicast information to mobile users, with mobile TV being the main service offered. The LTE infrastructure offers MBMS an option to use an uplink channel for interaction between the service and the user, which is not a straightforward issue in usual broadcast networks [1, 2].

In the context of LTE systems, the MBMS will evolve into e-MBMS ('e-' stands for evolved). This will be achieved through the increased performance of the air interface that will include a new transmission scheme called MBMS over a single frequency network (MBSFN). In MBSFN operations, MBMS data are transmitted simultaneously over the air from multiple tightly time-synchronized

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cells. A group of those cells, which are targeted to receive these data, is called the MBSFN area [2]. Because MBSFN transmission greatly enhances the signal-to-interference plus noise ratio (SINR), the MBSFN transmission mode leads to significant improvements in spectral efficiency (SE) in comparison with multicasting over the universal mobile telecommunications system. This is extremely beneficial at the cell edge, where transmissions (which in universal mobile telecommunications systems are considered as intercell 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 [1].

In this study, we evaluate the performance of MBSFN in terms of SE. In general, SE refers to the data rate that can be transmitted over a given bandwidth in a communication system. Several studies, such as [3], 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 as a certain block error rate (BLER) target to be achieved. Taking into account the above analysis, we focus on a dynamic user distribution, with users distributed randomly in the MBSFN area and therefore experiencing different SINRs. On the basis of the measured SINRs, our goal is to select the MCS that better suits each examined user deployment and should be used by the base stations when transmitting the MBMS data. Therefore, the major contribution of this paper is the proposal and evaluation of different MCS selection approaches that can be used during MBSFN transmission over LTE cellular networks.

The remainder of the manuscript is structured as follows: Section 2 presents the related work in the specific field; in Section 3, we describe the methodology for calculating the SE of the MBSFN delivery scheme in the single-user case; the approaches for selecting the MCS of an MBSFN area are presented in Section 4; the evaluation results are presented in Section 5; and finally, the conclusions and planned next steps are described in Sections 6 and 7, respectively. For the reader's convenience, Appendix A presents an alphabetical list of the acronyms used in the manuscript.

2. RELATED WORK

The performance of MBSFN has been thoroughly examined in previous research studies. However, most of them, such as [4–6], compare the performance of MBSFN transmissions with classic point-to-point and point-to-multipoint transmissions, in which the transmissions are executed in a per-cell basis with point-to-point or point-to-multipoint transport channels, respectively. Additionally, these studies do not consider adaptive modulation and coding in order to further improve the performance of MBSFN transmission.

Transmission techniques, which do not adapt to the fading channel, require a fixed link margin or coding to maintain acceptable performance in deep fades. Thus, these techniques are effectively designed for the worst-case channel conditions, resulting in insufficient utilization of the channel capacity [7]. For better utilization of the channel capacity, adaptive modulation and coding has been proposed in a variety of publications. For example, an adaptive variable rate variable-power transmission scheme using uncoded M-ary quadrature amplitude modulation was proposed in [8]. This adaptive technique is more power-efficient than nonadaptive modulation in fading.

Adaptive algorithms for the OFDM system were proposed in [9]. In [9], a multicell, multiuser OFDM system with an adaptive subcarrier allocation and an adaptive modulation was considered. The specific study describes an adaptive subcarrier, bit and power allocation algorithm to maximize the total throughput of the multicell system in the presence of co-channel interference, frequency selective Rayleigh fading and AWGN. For the unicast system, link adaptation is possible because the channel status information can be reported to the base station by the terminal. Our work expands [9], by focusing on the MBSFN service, which utilizes OFDM technology.

Moreover, studies such as [3, 10–13] have shown that SE is directly related to the MCS selected for the transmission. In [3] the authors proposed an approach, which selected the lowest MCS for the MBSFN transmission that allowed an expected SE target to be achieved for 95% of users. However, focusing only on the users' side may not be sufficient. Sometimes the operator's goal may be the maximization of the SE over all users of the topology or the provision of the service to all the users irrespective of the conditions of the users' experience. On the other hand, in [13] an adaptive MCS

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based on partial feedback was proposed in order to obtain an improvement on system throughput. Our work extends and completes the above studies and, furthermore, tackles the addressed problems by proposing four approaches, each one of them fulfilling different goals in terms of SE.

3. SINGLE-USER MCS SELECTION AND SPECTRAL EFFICIENCY ESTIMATION

To select the MCS and calculate the SE in the case of a single receiver, we use the following four-step procedure [14].

3.1. Step 1: signal-to-interference plus noise ratio calculation

Let the MBSFN area consist of N neighboring cells. Because of multipath, the signals of the cells arrive at the receiver by M different paths, so the average SINR of a single user at a given point m is expressed as in (1) [3]:

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

with

$$w(\tau) = \left\{\begin{array}{ll} 1 & 0 \leqslant \tau < T_{\mathrm{cp}} \\ 1-\frac{\tau-T_{\mathrm{cp}}}{T_{\mathrm{u}}} & T_{\mathrm{cp}} \leqslant \tau < T_{\mathrm{cp}}+T_{\mathrm{u}} \\ 0 & \text{otherwise} \end{array}\right\} \tag{2}$$

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.

The SINR is usually calculated in orthogonal frequency division multiple access for each subcarrier and all the SINRs are combined to find a nonlinear average SINR (effective SINR or γ_{eff}), using the exponential effective SIR mapping [15].

$$\gamma_{\mathrm{eff}} = EESM(\gamma_i, \beta) = -\beta \cdot In\left(\frac{1}{N}\cdot \Sigma_{i=1}^{N} e^{-\frac{SINR_i}{\beta}}\right) \tag{3}$$

where N is the number of subcarriers and β is calibrated by means of link level simulations to fit the compression function to the AWGN [15].

However, in 3GPP LTE systems, adjacent subcarrier allocation is considered, making subcarriers allocated to one channel experience similar fading conditions. All subcarriers allocated to a given channel will thus experience the same fast fading and their SINR will be equal [3].

3.2. Step 2: modulation and coding scheme selection

AWGN simulations were performed to obtain the MCS that should be used for the transmission of the MBSFN data to a single user. In general, the MCS determines both the modulation alphabet and the effective code rate of the channel encoder. Figure 1 shows the BLER results for channel quality indicators (CQI) 1–15 without using hybrid automatic repeat request and for the 1.4 MHz and 5.0 MHz bandwidths. The results were obtained from the link level simulator introduced in [15]. Each MCS is mapped to a predefined CQI value. The 15 different sets of CQIs and the corresponding MCSs are defined in [16].

In LTE networks, an acceptable BLER target value should be smaller than 10% [15]. 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 1. The 10% BLER values for each CQI are depicted in Figure 2. Using the obtained line, the γ_{eff} can be mapped to a CQI value (i.e., MCS) that should be signaled to the evolved Node B (e-NB or base station) so as to ensure the 10% BLER target.

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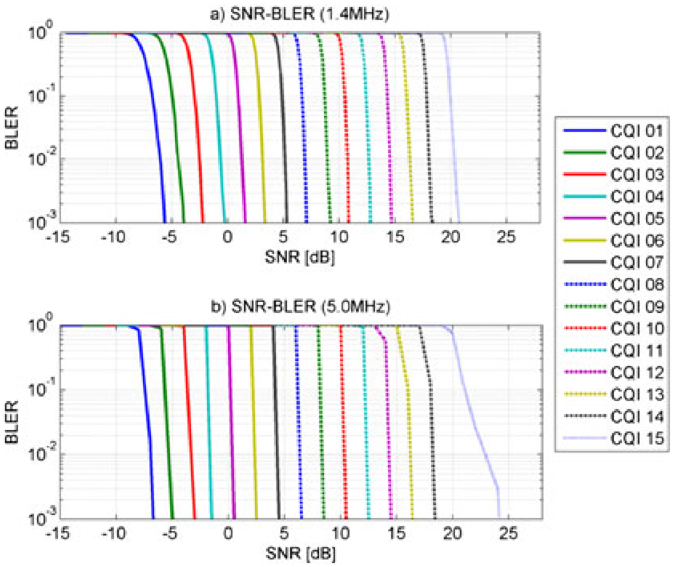

Figure 1. SNR–BLER curves obtained for: (a) 1.4 MHz and (b) 5.0 MHz.

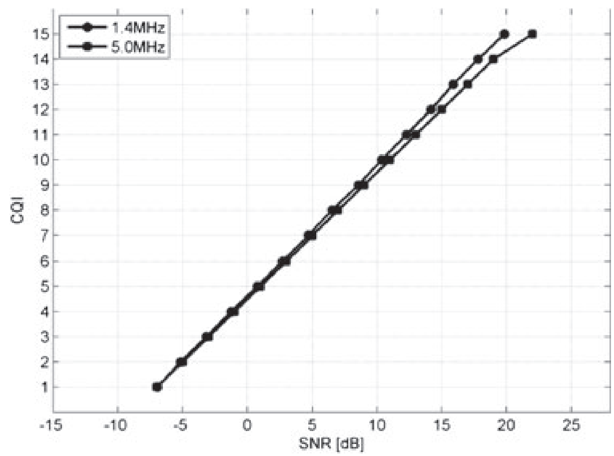

Figure 2. SINR to CQI mapping.

3.3. Step 3: throughput estimation

Equation (4) is used to estimate the achieved throughput for the selected MCS. In (4), *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 [17].

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

Therefore, by utilizing the SINR and MCS obtained by the SINR calculation (Step 1) and MCS selection (Step 2) steps respectively, the achieved throughput can be calculated. Figure 3(a) and (b) depict the relationship between the achieved throughput and the SNR for all MCSs, as calculated from (4) for the cases of 1.4 MHz and 5.0 MHz, respectively.

3.4. Step 4: single-user spectral efficiency

The 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

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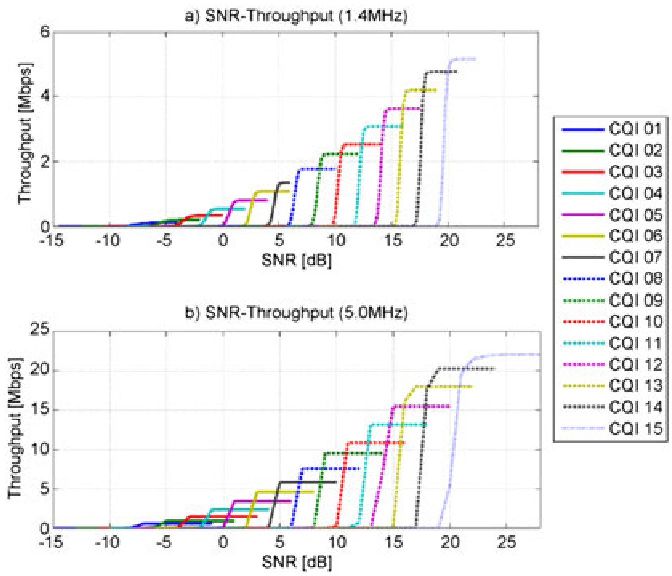

Figure 3. Throughput for all CQIs obtained for: (a) 1.4 MHz and (b) 5.0 MHz.

utilized. It can be obtained from the following equation:

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

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 5 dB and the bandwidth 5.0 MHz, from Figure 2 we obtain the equivalent CQI (CQI = 7). For the specific CQI and SINR value, the throughput as obtained from Figure 3 is 6 Mbps. Therefore, the SE as calculated from (5) is 1.2 bps/Hz.

4. MULTIPLE-USERS MCS SELECTION AND SPECTRAL EFFICIENCY ESTIMATION

The MCS selection and the SE evaluation in the multiple-users case are deduced from the single-user case described in the previous section. In general, when multiple users are located in the MBSFN area, the value of the total SE depends on the selected MCS. This section examines four approaches for the selection of the MCS during MBSFN transmissions. These approaches are carefully selected so as to match different users' deployments and media traffic conditions that could be realized in real word scenarios. More specifically, the selected approaches are listed below:

- The first approach selects the MCS that ensures that all users, even those with the lowest SINR, receive the MBSFN service (bottom-up approach).
- The second approach selects the MCS that ensures the maximum SE in the MBSFN area (top-down approach).
- The third approach sets a predefined SE threshold for the area and selects the MCS that ensures that the average SE over the MBSFN area exceeds this threshold (area-oriented approach).
- The fourth approach selects the MCS that ensures that at least the 95% of the users receive the MBSFN service with a predefined target SE (user-oriented approach).

As stated above, the first approach ensures that all users, even those with the lowest SINR, will receive the MBSFN service. This approach is suitable for real time multimedia transmissions in hot zones where hundreds of people are congregated. The second approach is met in cases where high demanding applications (e.g., high quality video streaming) are transmitted through MBSFN. In this case only users with high SLA will receive the service. The last two approaches are the most

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commonly used approaches. They appear in cases where a predefined threshold for the throughput should be ensured either at an area base (third approach) or at users' base (fourth approach). A more detailed analysis of the four MSC selection approaches is presented in the remainder of this section.

4.1. First approach — bottom-up approach

In this approach, the algorithm first calculates the SINRs for all the users in the topology and finds the minimum SINR value. Then the MCS that corresponds to the minimum SINR is obtained from the MCS Selection step (Figure 2). Finally, from (4) or Figure 3 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, irrespective of the conditions they experience (in terms of SINR). However, the fact that the user with the minimum SINR determines the MCS indicates that users with greater SINR values will not make use of a MCS that would ensure a greater throughput. The procedure for obtaining the MCS and the SE is presented using pseudocode in Algorithm 1 as follows.

Algorithm 1. Pseudocode of first approach.

```
Define MBSFN topology
% calculate the SINRs for all the users in the 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
selected_MCS = f_MCS (min_SINR)
% calculate the throughput for the selected MCS
throughput = f_throughput(selected_MCS, min_SINR)
% calculate the obtained spectral efficiency
Calculate SE
```

4.2. Second approach — top-down approach

The second approach selects the MCS that ensures the maximum average throughput and SE 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 in Figure 3. 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. Algorithm 2 presents the operation of the second approach using pseudocode.

4.3. Third approach — area-oriented approach

The goal of the third approach is to find the lowest MCS that achieves a target SE for an area. This target usually equals to 1 bps/Hz [3]. Initially the algorithm calculates the SINR value for each user. Then it proceeds with the scanning of the MCSs to calculate the per-user throughput. Starting from the lowest MCS, the algorithm calculates the per-user throughput and obtains the average throughput and the total SE for each MCS. If during the scanning procedure one MCS ensures that the total SE is equal or higher than the area target SE, the operation stops without scanning all the MCSs of Figure 3 and the algorithm selects this MCS for the delivery of the MBMS data. In other words, the

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Algorithm 2. Pseudocode of second approach.

```
Define MBSFN topology
% calculate the SINRs for all the users in the topology
FOR i = 1:total_users
    Calculate SINR(i)
END
% for each MCS 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 SE(MCS)
END
%find the max spectral efficiency that can be achieved
SE = max(SE(:))
```

Algorithm 3. Pseudocode of third approach.

```
Define MBSFN topology
Define area_target_SE
% calculate the SINRs for all the users in the topology
FOR i = 1:total_users
    Calculate SINR(i)
END
% scan the MCSs so as calculate the SE over the MBSFN area
FOR MCS = 1:15
    FOR j = 1:total_users
        throughput(MCS, j) = f_throughput (MCS, SINR(j))
    END
    % Calculate average throughput and spectral efficiency
    avg_throughput(MCS) = average(throughput(MCS, :))
    Calculate SE(MCS)
    % examine if area target SE is achieved
    IF SE(MCS) >= area_target_SE THEN      % target is achieved
        BREAK;
    ELSE      % target is not achieved
        SE = max(SE(:))
    END
END
% obtained spectral efficiency
SE = SE(MCS)
```


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goal of this approach is to find the lowest MCS that allows a target SE to be achieved. The scanning procedure starts from the lowest MCS in order to serve as many users as possible. If the scanning procedure started from the highest MCS, then the SE target would have been achieved very quickly by utilizing a high MCS, and therefore only the users that experience high SINRs would receive the MBSFN service as depicted in Figure 3. In the case when the target SE cannot be achieved, this approach has an identical operation with the second approach (i.e., selects the MCS that ensures the maximum total SE). This procedure is presented using pseudocode in Algorithm 3.

4.4. Fourth approach — user-oriented approach

The difference between the fourth and the third approaches is that in spite of defining an area-specific target SE such as the third approach, the fourth approach defines a user-oriented target SE (usually equal to 1 bps/Hz [3]). More specifically, the algorithm initially calculates the SINR value for each user. Then, starting from the lowest MCS, the algorithm calculates the per-user throughput and per-user SE of each MCS. If during the scanning procedure one MCS ensures that at least 95% of the users reach or exceed the target SE, the operation stops and the algorithm selects this MCS for the delivery of the MBMS data. Similar to the third approach, this one locates the lowest MCS that allows a user-specific target SE to be achieved for 95% of the users' population. If the target SE cannot be achieved for 95% of the users, the algorithm selects the MCS that ensures the maximum total SE. This procedure is presented using pseudocode in Algorithm 4.

Algorithm 4. Pseudocode of fourth approach.

```
Define MBSFN topology
Define user_target_SE
% calculate the SINRs for all the users in the topology
FOR i = 1:total_users
    Calculate SINR(i)
END
% scan the MCSs so as to calculate the per-user SE
FOR MCS = 1:15
    FOR j = 1:total_users
        % Calculate the per user throughput and spectral efficiency
        throughput(MCS, j) = f_throughput (MCS, SINR(j))
        SE(MCS, j) = throughput(MCS, j) / bandwidth
    END
    % examine if user target SE is achieved for 95% of users
    IF SE(MCS, j) >= user_target_SE FOR 95% of users THEN
        % target achieved
        BREAK;
    ELSE     % target is not achieved
        SE = max(SE(:, j))
    END
END
% obtained spectral efficiency
SE = SE(MCS, j)
```

5. PERFORMANCE EVALUATION

This section provides simulation results of the operation and performance of the aforementioned approaches. For the purpose of our experiments we have extended the link level simulator [15] in MATLAB (George Tsichritzis under the licence of Univ. of Patras, Greece). In particular, two different scenarios are investigated. Scenario 1 assumes that a constant number of 100 users are randomly distributed in the MBSFN area, while Scenario 2 investigates the case of variable number of users. The parameters used in the simulations are presented in Table I.

5.1. Scenario 1: predefined number of users

Scenario 1 attempts to make a direct comparison of the proposed approaches when the MBSFN area consists of a constant number of users. More specifically, the MBSFN area, which consists of four neighboring cells, contains 100 randomly distributed users. For comparison reasons the evaluation is performed for 1.4 MHz and 5.0 MHz bandwidths.

For the evaluation of the first approach, we first consider the case of 1.4 MHz bandwidth. According to the procedure described in paragraph 0, 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 –1.723 dB. Therefore, from Figure 2 CQI 3 is selected. Indeed, Figure 4(a) confirms that for the user with this value of SINR, CQI 3 can provide the maximum SE (0.233 bps/Hz) or equivalently from Equation (5) the maximum throughput (0.326 bps). An examination of Figure 4(b) leads to similar results. In this case however, the CQI that maximizes the SE of the user with the lowest SINR is CQI 4 (achieved SE equal to 0.473 bps/Hz), while the maximum achieved throughput is 2.365 bps. It is worth mentioning that the rest of the users in the MBSFN area will receive the MBMS service with the same throughput and SE, irrespective of the conditions they experience in terms of SINR.

The SE for all CQIs as calculated by the second approach is depicted in Figures 5(a) and (b) for 1.4 MHz and 5.0 MHz bandwidths, respectively. More specifically, both figures present the total SE per CQI after the scanning procedure. In both cases, the CQI that is selected after the scanning procedure is CQI 12, because it may achieve the highest value of total SE. In Figure 5(a) we notice that for the 1.4 MHz bandwidth and for the specific user distribution, the achieved SE is 2.200 bps/Hz. On the other hand, for the 5.0 MHz bandwidth the achieved SE is 2.630 bps/Hz (Figure 5(b)).

As depicted in Figure 6 the algorithm of the third approach 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 second approach, the scanning operation stops when the total SE reaches the target SE over the MBSFN area, which equals to 1 bps/Hz. As depicted in Figure 6(a) for 1.4 MHz bandwidth the first CQI that exceeds the SE target and therefore is selected for the transmission of the MBMS data, is CQI 8 that achieves 1.193 bps/Hz. On the other hand, in the case of the 5.0 MHz bandwidth, CQI 7 is selected and achieves a SE level of 1.109 bps/Hz.

Generally, the fourth approach has a similar performance to the third approach with small improvements in the achieved SE. Indeed, as illustrated in Figure 7, the algorithm scans the MCSs starting from the lowest MCS. However, contrary to the third approach, in the fourth approach the MCS selection is performed in a user-centered way. This means that for each of the scanned MCSs,

Table I. Simulation settings.

Parameter	**Value**
Cellular layout	Hexagonal grid, 19 cell sites
Inter site distance	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 / useful signal frame length	16.67μs / 66.67μs
Modulation and coding schemes	15 different sets defined in [16]

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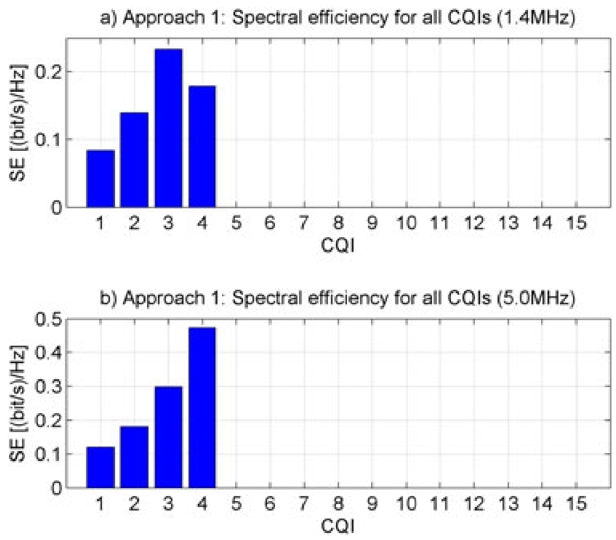

Figure 4. SE of the user with the lowest SINR for all CQIs (first approach) for: (a) 1.4 MHz and (b) 5.0 MHz.

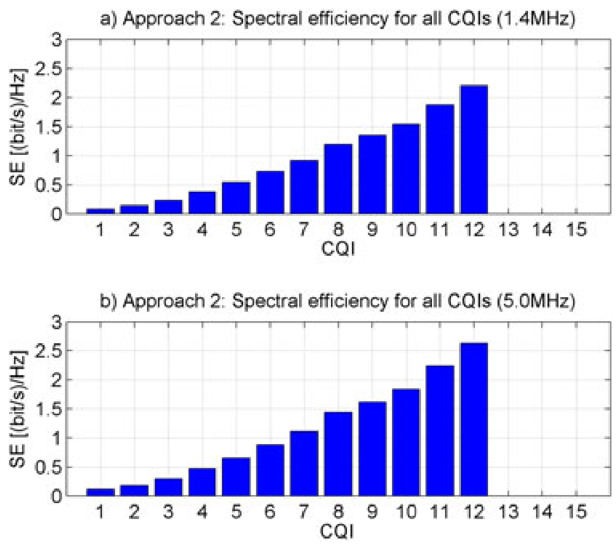

Figure 5. SE for all CQIs (second approach) for: (a) 1.4 MHz and (b) 5.0 MHz.

the algorithm calculates the per-user throughput and the equivalent per-user SE. The output of the scanning procedure indicates that in the case of 1.4 MHz, the first MCS that ensures that at least 95% of the users exceed the per-user SE target is CQI 8 (achieved per-user SE: 1.256 bps/Hz). In the case of 5.0 MHz, CQI 7 is selected (achieved per-user SE: 1.256 bps/Hz).

To sum up, the selected MCS and the achieved SE of each approach for the specific user distribution are depicted in Figure 8(a) and (b), for the 1.4 MHz and 5.0 MHz bandwidths, respectively. As expected, the second approach is capable of achieving the maximum SE. Moreover, Figure 8 confirms that the performance of the third approach is similar to the performance of the fourth one. The difference in the achieved SE is caused by the fact that the fourth approach does not take into account the 5% of users that experienced worse network conditions (in terms of SINR). Nevertheless, it is worth mentioning that both approaches reach the target SE that was set.

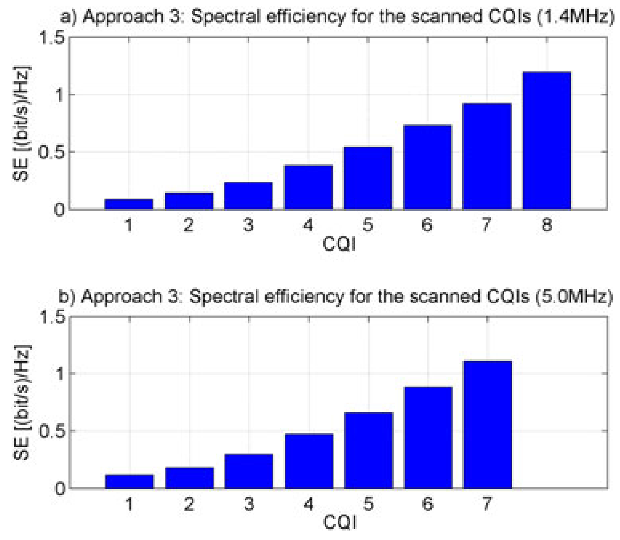

Figure 6. SE only for the CQIs scanned to reach the SE target over the area (third approach) for: (a) 1.4 MHz and (b) 5.0 MHz.

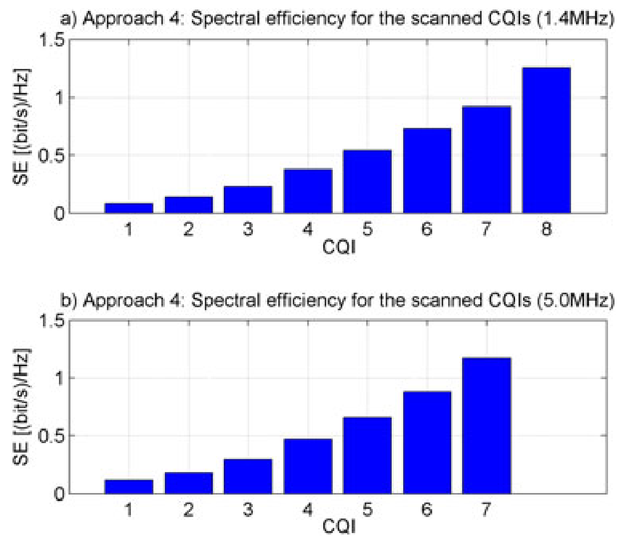

Figure 7. SE only for the CQIs scanned to reach the per-user SE target (fourth approach) for: (a) 1.4 MHz and (b) 5.0 MHz.

5.2. Scenario 2: variable number of users

This scenario presents simulation results concerning the operation of the proposed approaches for a variable number of users. 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 1.4 MHz and 5.0 MHz bandwidths, 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 are in accordance with Table I.

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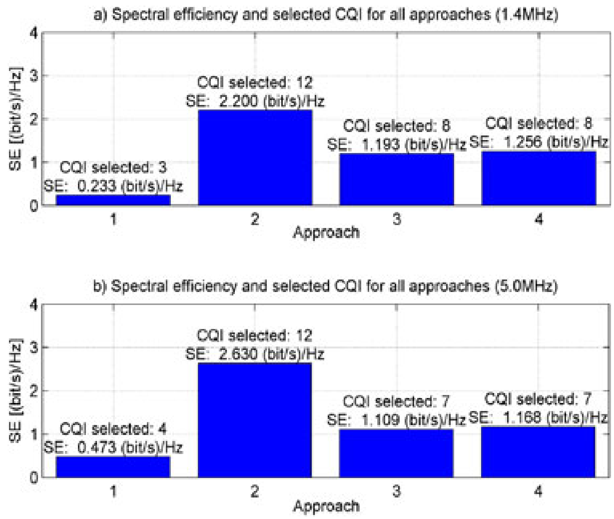

Figure 8. SE evaluation and CQI selection predefined number of users for: (a) 1.4 MHz and (b) 5.0 Mhz.

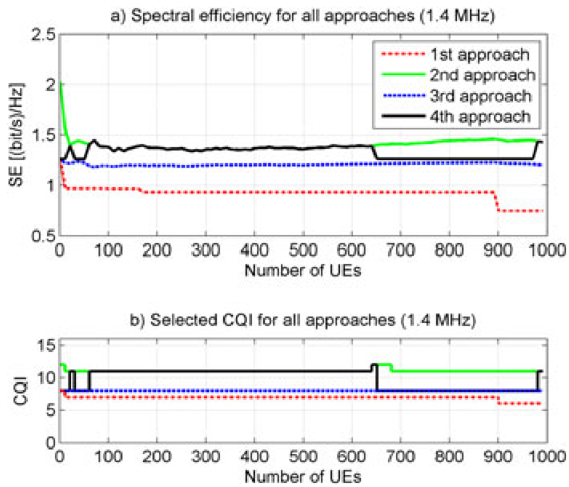

Figure 9. SE evaluation and CQI selection for variable number of users for 1.4 MHz.

As both figures show, the first 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 that ensures that even the users who experience low SINRs will receive the MBMS service. As a result, the users with better conditions will not receive the service with the highest possible throughput. Another disadvantage of this approach is that a potential mobility of the user with the lowest SINR could force the base station to continuously change the transmission MCS (ping–pong effect).

As depicted in Figure 9(a) and Figure 10(a), the second approach ensures the maximum SE irrespective of the users' population. This is reasonable because the second approach selects the MCS that ensures the maximum average throughput and SE over all users in the topology. It is also worth mentioning, that in certain scenarios where the majority of users are distributed near the base station, the second approach could achieve even higher values of SE. Indeed, the users near the base station experience high SINRs and as a consequence higher values of MCS may be utilized in order for a high average throughput to be achieved. On the basis of the above, we conclude that the second

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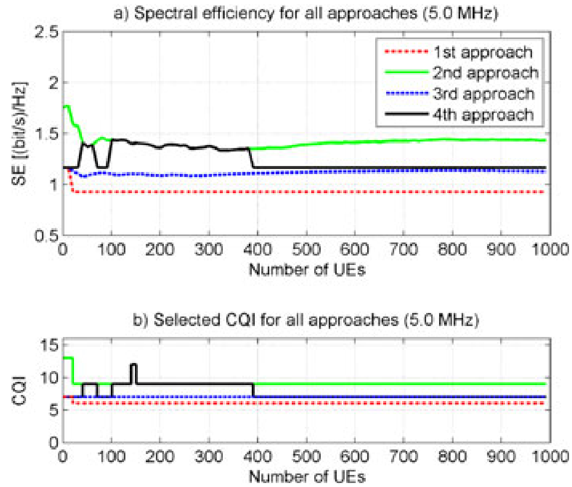

Figure 10. SE evaluation and CQI selection for variable number of users for 5.0 Mhz.

approach tends to utilize a high MCS. As stated in [18], this fact has the advantage of decreasing the users' transmit power. However, the users with bad conditions will not receive the MBMS service (see Figure 3).

The third approach selects the MCS that ensures that the average SE calculated over all users in the topology achieves the SE target. Therefore, as depicted in Figure 9 (1.4 MHz) the third approach utilizes CQI 8, while in Figure 10 (5.0 MHz) the selected CQI is CQI 7. The specific MCSs achieve a SE value over the MBSFN area higher than the SE target during the whole simulation (Figure 9(a) and Figure 10(a)). One of the most important advantages of the third approach is that it minimizes the ping-pong effect in MCS selection. Indeed, this approach ensures that the MCS will not necessarily change when the users' population changes. This leads to the avoidance of the ping-pong effect when new users enter the MBSFN topology or when users stop requiring the MBSFN service. However, it should be noted that the third approach does not achieve the maximum possible SE, because the algorithm scans the different MCS beginning from the lowest value of MCS and stops when the selected MCS achieves the SE target.

Finally, the fourth approach selects the MCS that satisfies the SE target for 95% of users. As depicted in Figure 9(a) and Figure 10(a), the specific MCSs achieve a SE value higher than the per-user SE target. Moreover, the SE achieved with this approach is higher than that of the third approach because 95% of the users receive the MBSFN service with a data rate that satisfies the SE target. This implies that the remaining 5% of users who experience bad conditions are not taken into account, in opposition to the third approach in which all the users in the MBSFN area are considered for the MCS selection.

To sum up, Table II presents a cumulative, direct comparison between the approaches analyzed in this manuscript. The main conclusion is that the selection of the most efficient MCS is

Table II. Qualitative comparison of the approaches.

Approach	Performance Throughput	Spectral efficiency	Service provision	MCS switching
First	Minimum	Minimum	Guaranteed	Medium
Second	Maximum	Maximum	Not Guaranteed	Medium
Third	Medium	Target over the area	Not Guaranteed	Minimum
Fourth	Medium	Target per-user	Not Guaranteed	Maximum

an operator-dependent parameter. Therefore, the uninterrupted service provision irrespective of the users' conditions would make the first 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 second approach. The third approach constitutes the most efficient approach when the operator targets a specific SE value over the MBSFN area and minimizes the ping-pong effect in MCS selection (minimum MCS switching). Finally, the fourth approach achieves a predefined per-user SE target for at least 95% of the users.

6. CONCLUSIONS

The main enhancement that the adoption of MBSFN brings in e-MBMS is the improvement of over-the-air SE. The achieved SE is mainly determined by the selected MCS in the physical layer. In this study, we have proposed four different approaches for the efficient selection of the appropriate MCS and we have evaluated the impact of this selection to the achieved SE. The parameters that have been taken into account in the evaluation are the number of served users and their position in the topology. On the basis of the above two parameters, the service provider can choose the most efficient MCS selection approach for the active MBSFN sessions. The approaches cover different scenarios that could be realized in the real world such as ensuring service continuity for the user with the lowest SINR value and therefore for all users in the MBSFN area, selecting the MCS that maximizes the SE, selecting the MCS based on the covered area or the percentage of the users that receive the service in an acceptable quality.

In brief, we could say that the selection of the appropriate MCS is an operator-dependent issue. Different operator requirements may lead to different MCS approach selection. To that end, service continuity can be secured by employing the first approach (bottom-up) , while for high demanding MBMS applications, which are targeted to users that experience optimal network and link conditions, the second approach (top-down) is the most efficient one. Additionally, ping-pong effect can be regulated by employing the third (area-oriented) approach and simultaneously, all MBMS users are treated by the approach as equal irrespective of the network and link conditions that they experience. Finally, the fourth approach (user-oriented) gives the ability to the network operator to predefine both the per-user target SE and the percentage of users that will be taken into account for the calculation of the achieved SE.

To conclude, it could be said that the analysis presented in this manuscript underlines that the introduction of an adaptive MCS selection algorithm for MBFSN-enabled LTE networks is a prerequisite for network operators in order to deploy high quality broadcast networks capable of delivering high demanding real time multimedia applications to mobile users.

7. FUTURE WORK

The step that follows this work could be the design, the implementation and the evaluation of an algorithm responsible for choosing the most efficient MCS selection approach according to operator needs each time. Our analysis indicates that switching approaches can possibly happen in real time. Furthermore, the combined usage of different approaches is also possible and could solve the particular inefficiencies that each approach has.

Another direction that we intent to investigate is the application of forward error correction (FEC) for MBSFN transmissions in LTE networks. FEC is an error control method that can be used to augment or replace other methods for reliable data transmission. The main attribute of FEC schemes is that the sender adds redundant information in the messages transmitted to the receiver. This information allows the receiver to reconstruct the source data. Such schemes inevitably add a constant overhead in the transmitted data and are computationally expensive. This additional communication cost will be calculated and based on this the efficiency of FEC use in different scenarios will be evaluated.

APPENDIX A: ACRONYMS

Acronym	Explanation
3GPP	3rd Generation Partnership Project
AMC	Adaptive Modulation and Coding
AWGN	Additive White Gaussian Noise
BLER	Block Error Rate
CCI	Co-Channel Interference
CP	Cyclic Prefix
CQI	Channel Quality Indicators
CSI	Channel Status Information
ECR	Effective Code Rate
EESM	Exponential Effective SIR Mapping
e-MBMS	evolved MBMS
e-NBs	evolved Node Bs
e-UTRAN	evolved UMTS Terrestrial Radio Access Network
FEC	Forward Error Correction
HARQ	Hybrid Automatic Repeat Request
ISD	Inter Site Distance
LTE	Long Term Evolution
MBMS	Multimedia Broadcast/Multicast Service
MBSFN	MBMS over Single Frequency Network
MCS	Modulation and Coding Scheme
M-QAM	M-ary Quadrature Amplitude Modulation
OFDMA	Orthogonal Frequency Division Multiple Access
PTM	Point-to-Multipoint
PTP	Point-to-Point
SE	Spectral Efficiency
SINR	Signal to Interference plus Noise Ratio
UMTS	Universal Mobile Telecommunications System

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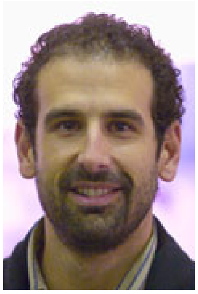

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