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A Dynamic MBSFN Area Formation Algorithm for Multicast Service Delivery in 5G NR Networks

Giuseppe Araniti, *Senior Member, IEEE,* Federica Rinaldi, *Student Member, IEEE,* Pasquale Scopelliti, *Member, IEEE,* Antonella Molinaro, *Member, IEEE,* and Antonio Iera, *Senior Member, IEEE*

***Abstract*—The ever-increasing demand for high-quality video contents over mobile networks is pushing Telco operators towards the design of new delivery solutions. 3GPP has defined Multimedia Broadcast/Multicast Service Single Frequency Network (MBSFN) to enable the simultaneous transmission of the same content within multiple cells over the same radio resources, with improved network scalability and spectral efficiency. This paper proposes a Dynamic MBSFN Area Formation (DMAF) algorithm that suitably selects the adjacent synchronized cells to include in any MBSFN Area of a 5G New Radio (NR) system to the purpose of increasing the system Aggregate Data Rate while avoiding user outage. The proposed algorithm dynamically creates MBSFN Areas by leveraging the multicast "subgrouping" paradigm for Scalable Video Coding (SVC) traffic delivery. Cells are grouped into different MBSFN Areas and any cell can be part of Disjoint MBSFN Area or Overlapping MBSFN Area. Each Overlapping MBSFN Area broadcasts a Base video flow at a given quality level to all users, whereas Enhancement Layers are only delivered to users with better channel conditions. Simulation results testify to the better performance achieved by the proposed algorithm w.r.t. other schemes available from the literature.**

***Index Terms*—5G, eMBMS, MBSFN, RRM, Multicast Subgrouping, Dynamic MBSFN Area Formation.**

I. Introduction

THE increasing number of smart devices encourages the demand for high-quality video content over mobile networks. Cisco analysis [1] forecasts that more than three-fourths of the world's mobile data traffic will be video by 2021; mobile video will increase 9-fold between 2016 and 2021, accounting for 78% of total mobile data traffic by the end of the forecast period.

With such an expected diffusion of bandwidth-hungry applications, mobile networks will tackle the challenges of guaranteeing high data rates and low latency to a large number of potential receivers. To cope with the consequent scalability issues, the Third-Generation Partnership Project (3GPP) standardized first Multimedia Broadcast/Multicast Service (MBMS) [2] and later evolved-MBMS (eMBMS) [3], which will also characterize the forthcoming next-generation technology known as 5G New Radio (NR) [4]. NR is designed to manage a huge number of service requests; specifically, it exploits eMBMS over Single Frequency Networks (MBSFN) [5] [6] to improve the system efficiency, by transmitting the same content at the same time over the same radio resources within nearby cells grouped in an MBSFN Area [7]. According to the 3GPP Legacy approach, all 5G base stations, namely gNodeBs (gNBs), of a given MBSFN Area need to be time-synchronized, in order to make cell-edge receivers experience an improved service quality by combining signals from different gNBs. All the users within an MBSFN Area receive the same broadcast content via the same Modulation and Coding Scheme (MCS), which determines the data rate. Therefore, in an MBSFN Area the user with the worst channel condition (i.e., worst Channel Quality Indicator (CQI) mapped onto a robust MCS) drives the system performance; this causes a spectral efficiency degradation to the system and a decrease in the satisfaction of the users receiving a low-quality video, although they are in good channel conditions.

With the advent of the 5G NR technology, MBSFN Areas should be dynamically arranged according to e.g. the service requirements, the user distribution, or a given cost function [6]. In the literature, the problem of dynamic area formation is not sufficiently investigated yet. Furthermore, 3GPP does not specify any algorithm for Area formation, which is therefore left open to the operators' decisions. Several open issues still concern the best selection of the cells clustered into the same MBSFN Area, the choice of contents to broadcast and users to include in an Area, as well as the design of effective radio resources management policies.

In line with the 3GPP recommendations [6], in this paper we propose a Dynamic MBSFN Area Formation (hereinafter referred to as "DMAF") algorithm that dynamically creates the MBSFN Areas in such a way as to increase the system Aggregate Data Rate (ADR), under the constraint that all users must be served through MBSFN, without any service outage. DMAF leverages Scalable Video Coding (SVC) [8] in combination with multicast "subgrouping" [9], [10]. Subgrouping consists in clustering multicast destinations into subsets, depending on their measured CQIs, and in simultaneously serving such subgroups at different data rates. In particular, DMAF creates several MBSFN Areas, according to user channel measurements, hence by taking into account the heterogeneity of the CQIs of the users and their geographical distribution across cells in the system. If two areas overlap then DMAF exploits the SVC technique to deliver Base and a set of Enhancement Layers of the video flow, respectively characterized by a given MCS. All users receive the Base Layer while users in good channel conditions receive both

G. Araniti, F. Rinaldi, P. Scopelliti, A. Molinaro, and A. Iera are with the DIIES Department, University Mediterranea of Reggio Calabria, Via Graziella Loc. Feo di Vito, 89100 Reggio Calabria, Italy (e-mail: araniti@unirc.it, federica.rinaldi@unirc.it, pasquale.scopelliti@unirc.it, antonella.molinaro@unirc.it, antonio.iera@unirc.it). G. Araniti is also with Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya St, Moscow, 117198, Russian Federation. A. Molinaro is also with Laboratoire des Signaux et Systèmes, CentraleSupélec–Université Paris-Saclay, France.

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Base and one or more Enhancement video layers.

The main contribution of this paper is the design of a heuristic algorithm for dynamic MBSFN area formation that enhances the system performance by: *(i)* choosing the best MBSFN Area configuration to increase the ADR; *(ii)* exploiting the multi-rate transmission typical of subgrouping jointly with the SVC technique, never used before for Area formation algorithms; *(iii)* performing radio resource allocation for an efficient spectrum utilization in the configured MBSFN Areas; *(iv)* guaranteeing total coverage with 100% served users. Results provided through simulations testify to the effectiveness of the proposed algorithm, which outperforms other MBSFN Area Formation approaches available from the literature.

The remainder of the paper is organized as follows. Section II provides a brief overview on MBSFN Area Formation solutions. The reference system model is described in Section III and our proposed DMAF algorithm in Section IV. Simulation results are illustrated in Section V. Conclusive remarks and hints for future works are summarized in Section VI.

II. Related Work

Multicast/Broadcast communications feature a wide range of applications (e.g., breaking news, alerts in emergency scenarios, live streaming of popular music or sport events, software updates) and will play an important role in 5G wireless systems [11].

The New Radio [4] access technology will be designed to support different kinds of Multicast/Broadcast applications: eMBMS [3], location/position-based and critical communication services [12], and Vehicle-to-Everything (V2X) services [13], [14]. To effectively support all these services, the International Telecommunication Union (ITU) [15] defined three usage scenarios: (i) enhanced Mobile Broadband (eMBB), (ii) massive Machine Type Communications (mMTC), and (iii) Ultra-Reliable and Low Latency Communications (URLLC). In this paper, we focus on the eMBB scenario, which supports eMBMS.

In the eMBMS architecture, the periodic user's CQI feedback is mandatory to determine the MCS level for multicast traffic delivery by the gNB towards that user. According to several solutions for Multicast traffic delivery in cellular systems, the user with the worst CQI in a multicast group drives the MCS selection for the entire group. According to this conservative approach, the content is broadcasted to all the multicast users with the same lowest data rate; this policy is fair but suffers from poor spectral efficiency. On the other hand, another algorithm [16] improves the spectral efficiency by privileging the service of the users with the highest CQI; this technique is affected by a lack of short-term fairness, although long-term fairness can be achieved. In-between these two opposite approaches, subgrouping, which we exploit in our MBSFN Area Formation procedure, has been introduced to trade off fairness and throughput. The multicast subgrouping scheme [9] consists in splitting multicast users into non-overlapping subgroups based on the CQI similarities and serving them at the proper MCS, which is the minimum supported in each subgroup. This technique exploits a multi-rate approach: users in good channel condition receive a higher data-rate service, whereas users in poor channel condition are able to decode low data-rate flows. In [17] authors demonstrated that the optimal subgroup configuration that maximizes the ADR is to be searched between a single subgroup and two-subgroups. Here, we apply that result to the case of MBSFN Area formation.

To the best of our knowledge, the MBSFN Area Formation problem [7] has been addressed in a few works. The *Legacy* approach considered by 3GPP [18] follows a conservative approach and includes all adjacent cells involved in the MBSFN transmission in a single MBSFN Area, without taking into account neither any users diversity nor their interests in specific contents. Differently, for Single Cell Point-to-Multipoint (SC-PtM), specified by 3GPP in [19], the number of MBSFN Areas in a Synchronization Area is the same as the number of cells. However, this approach does not fully exploit the Single-Frequency Network benefits.

Other works related to MBSFN, such as [20] and [21], focus on the best MBSFNs configuration in terms of performance. In [20], results show that the performance improves when the number of areas increases; nevertheless, the algorithm maximizes coverage and neglects the system throughput. The work in [21] shows that better performance is achieved by increasing the MBSFN Area size when the minimum separation among gNBs gets higher. Another recent work dealing with dynamic area formation is in [22]; it aims at maximizing the user quality of experience, considering the display capabilities of the user devices, but it does not address dynamic radio resource allocation or system throughput.

Among the most prominent works pursuing a *dynamic* approach to the area formation problem, the Single-Content Fusion (SCF) scheme [23] [24] has been proposed as a clustering heuristics for MBSFN Area Formation and content selection. SCF works in two steps; first, it creates single-content areas and then merges areas that significantly overlap. The result is a multi-content MBSFN that includes cells with very similar content interests and broadcasts the most demanded items, thus maximizing the system throughput via both multicast and unicast transmissions. In particular, SCF reduces the coverage of the MBSFN Area by transmitting the content at the highest MCS that can be received by users with good channel conditions. Users with poorer channel conditions (i.e., lower CQI) are then served through unicast links by sharing radio resources with the traditional unicast traffics. By doing so, SCF handles a mixed unicast and multicast traffic by dedicating up to 60 percent of available Radio Resources to MBMS transmission and the remaining 40 percent to unicast ones, following the 3GPP standard constraint defined in [25]. The risk is that, in the case of high load of traditional unicast traffic, the multicast users served through unicast links could not receive the content, thus suffering from service outage.

By starting from the cited literature works, in this paper we propose an algorithm for dynamic MBSFN Area formation and radio resource allocation, which overcomes the limitations of the 3GPP Legacy [18], SC-PtM [19] and SCF [23] [24] schemes. In particular, DMAF dynamically creates MBSFN Areas to satisfy requests by all users, with either bad or good channel conditions, and improves the system Aggregate Data

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Rate. This is achieved thanks to the multi-rate service delivery enabled by the multicast subgrouping technique [9], never exploited before in the area formation context, at the best of our knowledge.

III. System Model

We consider a reference MBSFN scenario, wherein a set $\mathcal{C}$ of cells (or gNBs), deployed within a Synchronization Area, is interested in delivering the same video content. A Synchronization Area [7] may include one or more MBSFN Areas, coordinated in such a way as to achieve an MBSFN transmission[1]. Let us denote by $\mathcal{M}$ the set of all MBSFN Areas activated over the Synchronization Area. Each MBSFN Area $m \in \mathcal{M}$ consists in adjacent cells that broadcast the same content at the same time over the same set of radio resources. Available radio resources are managed on a Resource Block (RB) basis. One RB is the smallest frequency resource that can be assigned to a User Equipment (UE); each RB corresponds to 12 consecutive and equally spaced sub-carriers. The NR access technology for 5G [26], supports multiple OFDM numerologies with the Subcarrier Spacing (SCS) taking different values (i.e., $\Delta f = 15 \div 480$ KHz) according to the following equation:

$$\Delta f = 15KHz \times 2^{\mu} \tag{1}$$

where μ is the numerology.
The NR scalable numerology also determines the Transmission Time Interval (TTI) ranging from 31.25 μs to 1 ms, as shown in Table I. In this work, we choose the numerology $\mu = 0$, that is the most suitable for eMBB applications delivered over eMBMS. The overall number of available RBs depends on both the system bandwidth configuration and the MCS.

TABLE I: scalable numerology. [26]

μ	$\Delta f = 2^{\mu} \times 15$ [KHz]	TTI [μs]
0	15	1000
1	30	500
2	60	250
3	120	125
4	240	62.5
5	480	31.25

Let $\mathcal{U}$ be the set of users interested in the broadcasted content. Each UE transmits its CQI feedback to the gNB. The CQI is associated to the maximum supported MCS [7], as reported in Table II.

The proposed DMAF algorithm creates several MBSFN Areas, which can be Overlapping or Disjoint. In a Disjoint MBSFN Area, a single video flow is broadcasted at the lowest MCS supported by the multicast receivers located in that MBSFN Area. In an Overlapping MBSFN Area, instead, all users receive the Base Layer while users in good channel conditions receive both the Base Layer and the maximum number of Enhancement video layers that is possible to carry with the available resources. The carried Enhancement Layers can be all, or a subset of, the defined video layers and constitute the set $\mathcal{L}$. This set is transmitted at a given MCS, which is the same for all the Enhancement layers.

[1]According to [7], an MBSFN transmission or a transmission in MBSFN mode is a simulcast transmission technique characterized by the transmission of identical waveforms at the same time from multiple cells.

TABLE II: CQI-MCS Mapping

CQI index	Modulation	Code rate x 1024	Minimum Rate [Kbps]
1	QPSK	78	25.59
2	QPSK	120	39.28
3	QPSK	193	63.34
4	QPSK	308	101.07
5	QPSK	449	147.34
6	QPSK	602	197.53
7	16QAM	378	248.07
8	16QAM	490	321.57
9	16QAM	616	404.26
10	64QAM	466	458.72
11	64QAM	567	558.72
12	64QAM	666	655.59
13	64QAM	772	759.93
14	64QAM	873	859.35
15	64QAM	948	933.19

Area formation in DMAF is driven by the multicast subgrouping technique [9], which clusters a multicast group of users in subgroups according to the similarity in their channel quality indicators.

In one of our previous works [17], we demonstrated that the optimal subgroup configuration that maximizes the system ADR includes either a single-group or two-subgroups. Extending this result, we assume that the users located in a Disjoint MBSFN Area belong to the same group and get only one video flow, while users located in an Overlapping MBSFN Area are split into two subgroups and receive the SVC-encoded video. In the latter case, the available radio resources (i.e., RBs) are split between the Base Layer and the set of transmitted Enhancement Layers. Users receiving the Enhancement Layer(s) also get the Base Layer, thus improving their perceived video quality.

Before formulating the area formation problem and the proposed heuristic implemented by DMAF, we summarize the main notations in Table III.

DMAF must meet the following constraints.

(i) MBSFN Area Constraints: Let us define the binary variables $y_{c,m}$, with $c = \{1, \ldots, C\}$ and $m = \{1, \ldots, M\}$, such that:

$$y_{c,m} = \begin{cases} 1, & \text{if the } c\text{-th cell belongs to the } m\text{-th MBSFN area} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

According to 3GPP [27], a cell can belong to at most 8 MBSFN Areas, i.e:

$$\sum_{m \in \mathcal{M}} y_{c,m} \leq 8 \quad \forall c \in \mathcal{C} \tag{3}$$

Within a Synchronization Area, the number of MBSFN Areas cannot exceed 256 [27], so:

$$|\ \mathcal{M}\ | \leq 256 \tag{4}$$

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TABLE III: Notation used in the proposed DMAF algorithm

$\mathcal{C}$	set of cell within the Synchronization Area
$\mathcal{M}$	set of all MBSFN Areas
m	*m*-th MBSFN Area belonging to $\mathcal{M}$
$y_{c,m}$	binary variable is equal to 1 if the *c*-th cell belongs to the *m*-th MBSFN Area otherwise it is equal to 0
$\mathcal{L}$	set of all transmitted Enhancement Layers
$\mathcal{U}$	set of users requiring the broadcasted service
$\mathcal{U}_j$	set of users belonging to the *j*-th cell
$\mathcal{U}_m$	set of users in the *m*-th MBSFN Area
$\mathcal{U}_{m,BL}$	users in the *m*-th area receiving the Base Layer
$\mathcal{U}_{m,EL}$	users in the *m*-th area receiving the set $\mathcal{L}$ of transmitted Enhancement Layers
$\mathcal{RB}_m$	RBs allocated to the *m*-th Disjoint MBSFN Area
$\mathcal{RB}_{m,BL}$	RBs for delivering the Base Layer in the *m*-th Overlapping MBSFN Area
$\mathcal{RB}_{m,EL}$	RBs for delivering all Enhancement Layers in the *m*-th Overlapping MBSFN Area
$\mathcal{RB}_{m,EL_l}$	RBs for delivering the *l*-th Enhancement Layer in the *m*-th Overlapping MBSFN Area
$\mathcal{C}_{out}$	set of cells with at least one user not supporting the reference CQI
$\mathcal{M}^{\mathcal{C}_{out}}$	set of MBSFN Area formed by considering the cells in $\mathcal{C}_{out}$
$m^{\mathcal{C}_{out}}$	*m*-th MBSFN Area belonging to $\mathcal{M}^{\mathcal{C}_{out}}$
$\mathcal{C}_{in}$	set of cells with at least one user supporting the reference CQI
$\mathcal{M}^{\mathcal{C}_{in}}$	set of MBSFN Area formed by considering the cells in $\mathcal{C}_{in}$
$m^{\mathcal{C}_{in}}$	*m*-th MBSFN Area belonging to $\mathcal{M}^{\mathcal{C}_{in}}$
$\mathcal{C}_{common}$	set of cells belonging to both $\mathcal{C}_{out}$ and $\mathcal{C}_{in}$
$\mathcal{C}_j$	set of cells excluded from $\mathcal{C}_{common}$ during the Cell Re-Clustering phase
$m^{\mathcal{C}_j}$	MBSFN Area formed by adjacent cells in $\mathcal{C}_j$
$\mathcal{ADR}$	Aggregate Data Rate of the system
$\mathcal{ADR}_m$	Aggregate Data Rate of the *m*-th Disjoint MBSFN Area
$\mathcal{ADR}_{m,BL}$	Aggregate Data Rate of the *m*-th Overlapping MBSFN Area delivering the Base Layer
$\mathcal{ADR}_{m,EL}$	Aggregate Data Rate of the *m*-th Overlapping MBSFN Area delivering the set $\mathcal{L}$ of transmitted Enhancement Layers
$\mathcal{M}_*$,$\mathcal{RB}_*$,$\mathcal{ADR}_*$	MBSFN Area and RB configuration with respective Aggregate Data Rate computed during the Cell Re-Clustering phase
R_{EL_l}	data rate of the *l*-th Enhancement Layer
$R_{minCQI(\mathcal{U}_m)}$	data rate associated to the minimum CQI within a set of users in the *m*-th Disjoint MBSFN Area
$R_{minCQI(\mathcal{U}_{m,BL})}$	data rate associated to the minimum CQI within a set of users receiving the Base Layer
$R_{minCQI(\mathcal{U}_{m,EL})}$	data rate associated to the minimum CQI within a set of users receiving the set $\mathcal{L}$ of Enhancement Layers

(ii) Resource Constraints: Let RB be the available amount of radio resources; we denote RB_{BL} and RB_{EL} the amount of RBs assigned to the Base and the Enhancement Layers, respectively. The overall amount of RBs allocated to the *m*-th MBSFN Area shall not exceed the number of available RBs in that MBSFN Area:

$$(\mid \mathcal{RB}_{m,BL} \mid + \mid \mathcal{RB}_{m,EL} \mid) \leq \mid \mathcal{RB}_m \mid, \quad \forall m \in \mathcal{M} \tag{5}$$

The sum of RBs allocated to the *m*-th MBSFN Area for delivering all the *l*-th Enhancement Layers shall not exceed the number of available RBs destined to transmit the set of Enhancement Layers in that MBSFN Area:

$$\sum_{l \in \mathcal{L}} \mid \mathcal{RB}_{m,EL_l} \mid \leq \mid \mathcal{RB}_{m,EL} \mid, \quad \forall l \in \mathcal{L} \tag{6}$$

where the amount of RBs allocated to deliver the *l*-th Enhancement Layer in the *m*-th MBSFN Area is the ratio between the data rate of the *l*-th Enhancement Layer and the data rate related to the MCS for the transmission of the set of Enhancement Layers, so:

$$\mid \mathcal{RB}_{m,EL_l} \mid = \left\lceil \frac{R_{EL_l}}{R_{minCQI(\mathcal{U}_{m,EL})}} \right\rceil, \quad \forall l \in \mathcal{L} \tag{7}$$

(iii) Layers Constraints in Overlapping MBSFN Areas:

The Base Layer shall be delivered to all the users of a given Overlapping MBSFN Area:

$$\mathcal{U}_{m,BL} = \mathcal{U}_m, \forall m \in \mathcal{M} \tag{8}$$

where $\mathcal{U}_{m,BL}$ is the set of users in the *m*-th Overlapping MBSFN Area receiving the Base Layer.

The set of Enhancement Layers shall be delivered to a subset of $\mathcal{U}_{m,BL}$:

$$\mathcal{U}_{m,EL} \subseteq \mathcal{U}_{m,BL}, \forall m \in \mathcal{M} \tag{9}$$

where $\mathcal{U}_{m,EL}$ is the set of users in the *m*-th Overlapping MBSFN Area receiving also the Enhancement Layer(s).

Our purpose is to create MBSFN Areas that meet the above constraints and to dynamically assign radio resources in order to maximize the overall ADR in the Synchronization Area. Given a set $\mathcal{M}$ of MBSFN Areas, the ADR is given by:

$$\mathcal{ADR} = \sum_{m \in \mathcal{M}} \big((\mathcal{ADR}_{m,BL} + \mathcal{ADR}_{m,EL}) + \mathcal{ADR}_m \big) \tag{10}$$

where

$$\mathcal{ADR}_{m,BL} = \sum_{u \in \mathcal{U}_{m,BL}} R_{minCQI(u)} \times \mid \mathcal{RB}_{m,BL} \mid, \forall m \in \mathcal{M} \tag{11}$$

is the aggregate data rate of users receiving the Base Layer,

$$\mathcal{ADR}_{m,EL} = \sum_{u \in \mathcal{U}_{m,EL}} \sum_{l \in \mathcal{L}} R_{minCQI(u)} \times \mid \mathcal{RB}_{m,EL_l} \mid, \tag{12}$$

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$$\forall m \in \mathcal{M}, \forall l \in \mathcal{L}$$

is the sum of data rates achieved by the delivery of the Enhancement Layer(s), and

$$\mathcal{ADR}_m = \sum_{u \in \mathcal{U}_m} R_{minCQI(u)} \times \mid \mathcal{RB}_m \mid, \forall m \in \mathcal{M} \quad (13)$$

is the aggregate data rate of users within each MBSFN Disjoint Area receiving a single video flow (non-SVC encoded), at the MCS corresponding to the mimimum CQIs measured by users in the Area. It is worth remarking that if the m-th MBSFN Area belongs to Overlapping MBSFN Areas, then $\mathcal{ADR}_m = 0$. Conversely, if the m-th MBSFN Area is disjoint, then $\mathcal{ADR}_{m,BL} = \mathcal{ADR}_{m,EL} = 0$.

Since the MBSFN Area formation problem is NP-hard, with DMAF algorithm we propose a heuristic approach to solve the following problem:

$$\arg\max_{\mathcal{RB}} \mathcal{ADR} \quad (14)$$

subject to (2) - (10)

while serving 100% of users interested in the broadcast content.

Below, a sample illustration is given to help to understand the proposed system model.

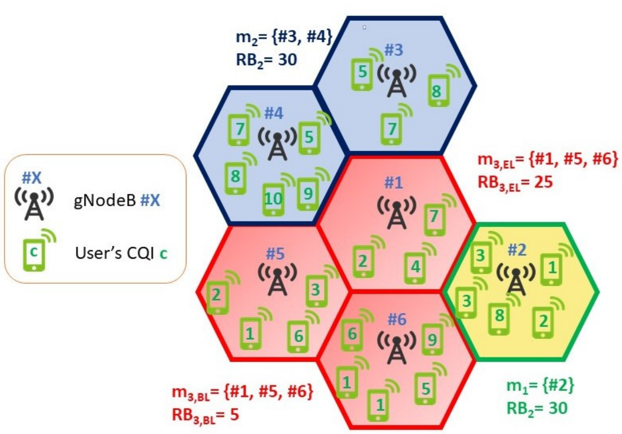

Fig. 1: Illustration of the system model.

We consider a simple system with 6 cells; 30 RBs are available for MBSFN transmission. Let us consider that the CQIs measured by each user in each cell are reported in Fig. 1.

The execution of the DMAF algorithm will result in the formation of three MBSFN Areas: $m_1 = \{\#2\}$, $m_2 = \{\#3, \#4\}$, $m_{3,BL} = \{\#1, \#5, \#6\}$ and $m_{3,EL} = \{\#1, \#5, \#6\}$.

m_1 (green cells) and m_2 (blue cells) are Disjoint MBSFN Areas; since they transmit a single video flow, all available RBs can be assigned to the MBSFN transmission (i.e., $RB_1 = RB_2 = 30$).

$m_{3,BL}$ and $m_{3,EL}$ (red cells) represent the Overlapping MBSFN Area delivering the Base Layer and the Enhancement Layer(s), respectively. To avoid the interference among the video layers transmitted in the Overlapping MBSFN Area the radio resources must be split into such cells. Hence, the minimum amount of RBs to guarantee a minimum data rate is assigned to deliver the Base Layer (in the example, $RB_{3,BL}$ is equal to 5); whereas all remaining radio resource are allocated for the delivery of the Enhancement Layers ($RB_{3,EL} = 25$). It is worth noting that the number of Enhancement video layers that can be delivered depends on the data rate associated to each layer of the specific video service.

IV. DMAF Algorithm

Since the problem of finding the best set of MBSFN Areas where delivering the eMBB service through several video layers is NP-hard, we propose DMAF as a heuristic approach to solve the problem of MBSFN Area formation.

The objective of DMAF is to define the configuration of MBSFN Areas $\mathcal{M}$ and to assign the relative radio resources RBs to users in these MBSFN Areas in order to maximize the system ADR.

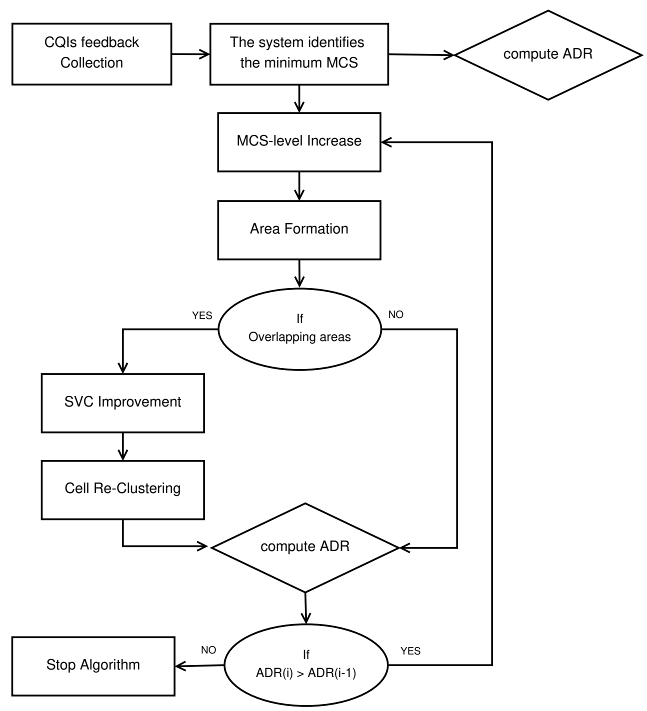

Fig. 2: Block diagram of DMAF algorithm.

DMAF initially groups all the cells, where users are interested in the same Multicast service, into a single MBSFN Area where the content can be broadcasted with the most robust MCS supported by all users. The area formation proceeds by steps, by increasing the MCS by one at each step. At each step i, MCS i is considered, the potential MBSFN Areas are identified, and the resulting ADR for the system is computed. The procedure exits when the computed ADR at step (i+1) is lower than the ADR at step i, or all MCS values have been examined (i.e., current MCS=15). As shown in Figure 2, the DMAF algorithm involves the following phases:

- **Initialization Phase:** this phase includes CQI collection and MBSFN Area initialization. The system collects the

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CQI feedbacks from all users belonging to the Synchronization Area and identifies the MBSFN Area based on the minimum MCS supported by all users. This step is the same as in the Legacy approach and guarantees to serve 100% of users.

- **MCS-level Increase**: DMAF iteratively increases the MCS level of the multicast transmission to improve the system ADR.
- **Area Formation**: DMAF opportunely clusters the cells according to the user channel quality similarities and creates a new MBSFN Area configuration able to support all multicast users. Such areas can be Disjoint and/or Overlapping. In the case of Disjoint MBSFN Areas, a single flow will be delivered at the lowest MCS supported by users in such areas. This allows to achieve a higher ADR with respect to the Legacy approach. In the case of the Overlapping MBSFN Areas, the *SVC Improvement* and the *Cell Re-Clustering* phases are carried out.
- **SVC Improvement**: in the Overlapping MBSFN Areas a SVC encoded video flow is delivered through the Base layer and a set of Enhancement Layers in order to improve the perceived video quality and to increase the data-rate of users with good channel conditions, and consequently the system ADR. Hence, within each Overlapping MBSFN Area, multicast users are split into two subgroups where users in good channel conditions receive the Base plus the Enhancement Layer(s), whereas users in poor channel conditions can decode only the Base Layer.
- **Cell Re-Clustering**: DMAF identifies and removes one by one the cells within the Overlapping MBSFN Area that could negatively affect the system ADR. Such cells form new Disjoint MBSFN Areas.

At the end of each iteration, if the obtained ADR is greater than the ADR of the previous step, then the new MBSFN Areas configuration is selected and DMAF continues to iterate from phase 2 by increasing the MCS-level. Otherwise, the new MBSFN Area configuration is discarded and the algorithm stops. The algorithm for area formation is periodically run; the operator can set this periodicity. Decisions on MBSFN area formation can be taken with a high frequency (e.g., TTI, or every given number of time frames), or with a medium-to-low frequency (e.g., once every few hours, as suggested in [24]). The cost of this dynamic computation is kept reasonable, as explained in section IV-B.

Algorithm 1 DMAF

1: **Define:** $C = \{C_j : j = 1, \ldots, w\}$ the set of cells with users requesting the same content;
2: **Define:** $U = \{U_i : i = 1, \ldots, n\}$ set of n users;
3: **Define:** $U_j = \{U_{ij} : i = 1, \ldots, s\} \subseteq U$ set of s ($s \leq n$) users belonging to the j-th cell;
4: **Define:** $\mathcal{M} = \{m_k : k = 1, \ldots, t\}$ set of MBSFN Areas;
5: **Define:** *cqi*, the reference CQI;
6: **Define:** C_{out} the set of cells with at least 1 users not supporting the reference *cqi* (i.e., $minCQI(C_j) < cqi$);
7: **Define:** C_{in} the set of cells with at least 1 user whose CQI $\geq$ *cqi*;
8: **Define:** $C_{common} = C_{out} \cap C_{in}$ set of cells with both users experiencing CQI $<$ *cqi* and users with CQI $\geq$ *cqi*;
9:
10: $CQI(U) = CQIcollection(U)$;
11: **MCS-level Increase:**
12: **for** $\{cqi = 1 \rightarrow 15\}$ **do**
13: **for** $C_j \in C$ **do**
14: **if** $\{\exists CQI(U_{ij}) < cqi\}$ **then**
15: **add** C_j to C_{out};
16: **end if**
17: **if** $\{\exists CQI(U_{ij}) \geq cqi\}$ **then**
18: **add** C_j to C_{in};
19: **end if**
20: **end for**
21: $\mathcal{M} = AreaFormation(C_{in}, C_{out})$;
22: **if** $C_{common} \neq \emptyset$ **then**
23: $\mathcal{M}, RB, ADR = SVCimprovement(\mathcal{M})$;
24: $\mathcal{M}_*, RB_*, ADR_* = CellReclustering(\mathcal{M})$;
25: **if** $ADR_* \geq ADR$ **then**
26: $ADR = ADR_*, RB = RB_*, \mathcal{M} = \mathcal{M}_*$;
27: **end if**
28: **else if** $C_{common} = \emptyset$ **then**
29: $RB = AllocateRB(\mathcal{M})$;
30: $ADR = ComputeADR(\mathcal{M}, RB)$;
31: **end if**
32: **if** $ADR_{cqi} \geq ADR_{cqi-1}$ **then**
33: $ADR = ADR_{cqi}, RB = RB_{cqi}, \mathcal{M} = \mathcal{M}_{cqi}$;
34: **else**
35: break;
36: **end if**
37: **end for**
38: **return:** $\mathcal{M}, RB, ADR$.

A. Step-by-step implementation

Algorithm 1 lists the pseudocode of DMAF algorithm.

1) MCS-level Increase: After collecting all user CQI feedbacks (line 10), the *MCS-level Increase* phase begins. The algorithm iteratively increases the reference *cqi* from the minimum CQI index recorded in the Synchronization Area to the maximum value achievable by the system (i.e., 15 [28]). It is worth noticing that, given *cqi* i, the same value i is associated to the supported MCS level, hence, the increase of the reference *cqi* corresponds to the increase of the MCS-level. At each iteration, cells are grouped according to the CQIs experienced by their users. Two cell groups are created: one (i.e., C_{in}) including all cells where at least one user supports the reference *cqi*, while the other one (i.e., C_{out}) including cells where at least one user does not support the reference *cqi* (lines 13-20). This means that cells belonging only to C_{in} can support the increase in the MCS level decided by the current reference *cqi*, whereas for the remaining cells, the minimum *cqi* determines the supported MCS. Following this cells splitting, Disjoint and/or Overlapping MBSFN Areas are created according to Algorithm 2 - *Area formation* satisfying the adjacency constraints. Subsequently, if Overlapping MBSFN Areas are created, Algorithm 3 - *SVC Improvement* and Algorithm 4 - *Cell Re-Clustering*, are carried out (lines 22-27); the video content is broadcasted at two different MCS levels, for the Base Layer and the set of Enhancement Layers, respectively, decided according to the joint combination of multicast subgrouping and SVC techniques. On the contrary, if Disjoint MBSFN Areas are created, then all available RBs are used to deliver the content to each MBSFN Area at the selected MCS level, i.e., the minimum supported in a given area, (lines 28-31). Algorithm 1 stops when the computed ADR on the current iteration is lower than that of the previous

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iteration, no matter how much lower it is (lines 30-34). It is worth highlighting that, until the ADR stops to increase, the observed increase in ADR at the generic $(i+1)$-th iteration is not marginally greater then the one observed at the previous iteration. Hence, continuing to iterate until the configuration with the highest achievable ADR is found is definitely worth the cost.

The algorithm terminates (lines 37-38) and provides the set $\mathcal{M}$ of MBSFN Areas, the number of RB to be assigned to each MBSFN Area, and the ADR.

Algorithm 2 Area Formation

if $VerifyAdjacency(C_{in}) == True$ **then**
  $\mathcal{M}^{C_{in}} = CreateMBSFNArea()$;
end if
if $VerifyAdjacency(C_{out}) == True$ **then**
  $\mathcal{M}^{C_{out}} = CreateMBSFNArea()$;
end if
$\mathcal{M} = \mathcal{M}^{C_{in}} \cup \mathcal{M}^{C_{out}}$;
return: $\mathcal{M}$.

2) Area Formation: Objective of this phase is to group cells belonging to C_{out} and C_{in}, in order to create proper MBSFN Areas. The Area Formation procedure takes as inputs the two sets of cells, C_{out} and C_{in}, and checks whether there is an adjacency among the cells belonging to the two sets. Each group of adjacent cells in the two sets forms an MBSFN Area. The output of this phase is the set $\mathcal{M}$ of Disjoint and/or Overlapping MBSFN Areas. $\mathcal{M}$ is given by two sub-sets of MBSFN Areas $\mathcal{M}^{C_{out}}$ and $\mathcal{M}^{C_{in}}$, where video flows can be broadcasted at standard and high quality, respectively. The areas within $\mathcal{M}^{C_{in}}$ will support transmissions with greater spectral efficiency, according to the *reference cqi*; whereas the transmissions in the areas belonging to $\mathcal{M}^{C_{out}}$ will be driven by users with the minimum cqi.

Algorithm 3 SVC Improvement

1:
2: **if** $C_{common} \neq \emptyset$ **then**
3:   **for** $C_c \in C_{common}$ **do**
4:     **let** $m^{C_{in}} \in \mathcal{M}^{C_{in}}$, $m^{C_{out}} \in \mathcal{M}^{C_{out}}$;
5:     $m^{C_{out}}(C_c) = m^{C_{out}}(C_c) \cup m^{C_{in}}(C_c)$;
6:   **end for**
7:   $\mathcal{M} = \mathcal{M}^{C_{in}} \cup \mathcal{M}^{C_{out}}$;
8:   $RB = AllocateRB(\mathcal{M})$;
9:   $ADR = ComputeADR(\mathcal{M})$;
10: **end if**
11: **return:** $\mathcal{M}, RB, ADR$.

3) SVC Improvement: Algorithm 3 shows the pseudocode of the SVC Improvement phase. It is performed to deliver the Base Layer and the Enhancement Layer(s) over the Overlapping MBSFN Area (lines 3-6). The Enhancement Layers are delivered at the MCS level equal to the reference *cqi*, whereas the Base Layer is transmitted at the lowest MCS supported by all users within the area. Due to the presence of different flows over the same region, interference between the two flows could occur if radio resources are not properly assigned. Hence, the RBs are split to avoid the interference; this means that a subset of RBs is dedicated to the delivery of the Base video layer and another one is allocated to deliver the Enhancement video layers. This RB splitting is implemented in the whole Overlapping MBSFN Area (line 8). Then, the ADR is computed (line 9). The network decides the number of Enhancement Layers that can be transmitted in the RBs assigned to the users with good channel quality on the basis of the specific video flow. Thanks to SVC, they perceive a better video quality and increase their data rates by exploiting the whole available bandwidth. According to this approach, users in poor channel conditions are served at lower datarate but are nonetheless served; hence, 100% of users are covered without service outage. Users experiencing good channel conditions can receive the Base and the set of Enhancement Layers achieving a higher spectral efficiency (i.e., higher MCS) with respect to the Legacy approach.

Algorithm 4 Cell Re-Clustering

1:
2: **let** $m^{C_{in}} \in \mathcal{M}^{C_{in}}$, $m^{C_{out}} \in \mathcal{M}^{C_{out}}$;
3: **for** $C_j \in C_{common}$ **do**
4:   $m_*^{C_{in}} = m^{C_{in}}(C_j)\backslash\{C_j\}$;
5:   $m_*^{C_{out}} = m^{C_{out}}(C_j)\backslash\{C_j\}$;
6:   **create** $m^{C_j} = C_j$;
7:   $\mathcal{M}_*^{C_{in}}, \mathcal{M}_*^{C_{out}} = AreaFormation(m_*^{C_{in}}, m_*^{C_{out}})$;
8:   $\mathcal{M}_* = \mathcal{M}_*^{C_{in}} \cup \mathcal{M}_*^{C_{out}} \cup m^{C_j}$;
9:   $RB_* = AllocateRB(\mathcal{M}_*)$;
10:   $ADR_* = ComputeADR(\mathcal{M}_*, RB_*)$;
11:   **if** $ADR_* \geq ADR$ **then**
12:     $ADR = ADR_*$;
13:     $RB = RB_*$;
14:     $\mathcal{M} = \mathcal{M}_*$;
15:   **end if**
16: **end for**
17: **return:** $\mathcal{M}, RB, ADR$.

4) Cell Re-Clustering: Algorithm 4 presents the Cell Re-Clustering procedure. Its aim is to find other possible MBSFN Area configurations in order to further increase the system ADR in the case of overlapping MBSFN Areas. The Cell Re-Clustering phase attempts to increase the overall ADR by taking away from the Overlapping MBSFN Areas the cells negatively affecting the system performance (lines 4-5). Specifically, the algorithm removes those cells belonging to C_{common}, hence to both C_{out} and C_{in} (line 3). Whenever a cell is removed, it will be part of an existing MBSFN Area or it will form a new MBSFN Disjoint Area (line 6). Then, the Cell Re-Clustering checks if the remaining cells are still adjacent to form an MBSFN Area through the Area Formation phase (line 7). RBs are allocated to the MBSFN Areas of the new configuration (lines 8-9) in order to further enhance the system ADR, which is recomputed in the line 10. Therefore, in the case of Overlapping MBSFN Areas, Cell Re-Clustering checks whether it is better to deliver a single layer or more scalable layers through Disjoint MBSFN Area or Overlapping MBSFN Area, respectively. The outputs are the new set $\mathcal{M}$ of Disjoint MBSFN Area and/or Overlapping MBSFN Areas and the proper set RB of radio resources that further improve the system performance in terms of ADR.

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B. Complexity of DMAF algorithm

We provide a detailed analysis of the computational cost for running DMAF algorithm by evaluating the complexity for each phase (CQI Collection, MCS-level Increase, Area Formation, SVC Improvement, and Cell Re-Clustering).

1) CQI collection: The collection of user CQI feedbacks has a computational cost of O($|\mathcal{U}|$), where $|\mathcal{U}|$ is the number of users.

2) MCS-level Increase: It provides two partitions of the whole set of cells in the system, according to the channel conditions experienced by all users. This task linearly depends on the number of cells (i.e., $|\mathcal{C}|$) and on the number of users interested in the broadcasted content (i.e., $|\mathcal{U}|$) with a complexity of O($|\mathcal{C}||\mathcal{U}|$).

3) Area Formation: The MBSFN Area formation (i.e., $\mathcal{M}^{C_{in}}$ and $\mathcal{M}^{C_{out}}$) is based on the verification of the adjacency among cells and has a complexity of O($|\mathcal{C}|^2$), where $|\mathcal{C}|$ is the number of cells in the system. The computation of the set $|\mathcal{M}|$ of MBSFN Area including the areas belonging to both $\mathcal{M}^{C_{in}}$ and $\mathcal{M}^{C_{out}}$ has a complexity of O(2*$|\mathcal{C}|$), hence O($|\mathcal{C}|$). The overall complexity of Area Formation is O($|\mathcal{C}|^2$).

4) SVC Improvement: This procedure has a complexity of O($|\mathcal{C}|$). The generation of the new set $\mathcal{M}$ of MBSFN Area, formed by all new areas of $\mathcal{M}^{C_{in}}$ and $\mathcal{M}^{C_{out}}$, has a complexity of O($|\mathcal{C}|$), the same complexity of the allocation of radio resources to all the MBSFN Areas. The computational cost of the ADR is O($|\mathcal{U}|$), where $\mathcal{U}$ is the number of users in the system. Therefore, the execution of Algorithm 3 has a complexity of O($|\mathcal{C}| + |\mathcal{U}|$).

5) Cell Re-Clustering: Cells, which negatively affect the system performance, are removed from the Overlapping MBSFN Areas, one by one, with a complexity of O($|\mathcal{C}|$). After verifying the adjacent constraint, these cells will form another MBSFN Area with a complexity of O($|\mathcal{C}|^2$). Therefore, the overall complexity of Algorithm 4 is O($|\mathcal{C}|^3$).

in the case of only Disjoint MBSFN Areas, the MCS-level Increase continues by allocating radio resources and computing the ADR with a complexity of O($|\mathcal{C}|$) and O($|\mathcal{U}|$), respectively.

After computing the system $\mathcal{ADR}$ for the created configuration of MBSFN Areas, MCS-level Increase runs at most k times, where $k = 15$ is the number of available CQI.

The implementation of DMAF algorithm has a polynomial complexity equal to O($|\mathcal{C}||\mathcal{U}| + |\mathcal{C}|^3$). This computational complexity is reasonable and makes DMAF feasible in real-world scenarios with high performing gNBs executing the proposed algorithm in a feasible runtime.

Furthermore, the DMAF heuristics iteratively finds the solution that maximizes the system ADR in a finite number of steps, limited by the maximum number of available MCS levels (i.e., 15), hence, it converges to a solution in a finite time.

V. Performance Evaluation

A. Simulation Model

To demonstrate the effectiveness of the proposed DMAF algorithm, simulations are performed by means of the MATLAB tool, according to the guidelines for the coordinated multicell system model defined in [29]. We consider a 57-cells scenario, typically used by 3GPP [23]. The coverage radius of each gNB is 250 m. The gNB transmit power is 46 dBm and its antenna gain is 15 dBi. For the UE, the antenna gain is 0 dBi. Table IV lists the main simulation settings.

TABLE IV: Main Simulation Assumptions

Parameter	Value
Environment	Macro cell, Urban area, coordinated deployment
Cell layout	Hexagonal grid, 57 cells [23]
Inter Site Distance	500 m
Pathloss model	128.1+37.6 log_{10}(R), R in kilometers
gNB transmit power	46 dBm
gNB antenna gain	15 dBi
UE antenna gain	0 dBi
gNB noise figure	5 dB
UE noise figure	9 dB
Carrier frequency	2 GHz
Scheduling Frame	10 ms
RB size	12 sub-carrier, 0.5 ms
μ	0
Sub-carrier spacing	15 kHz
TTI	1 ms
BLER target	1%

Users are randomly distributed within the Synchronization Area and their position is assumed to be constant. We consider that cells belonging to the same MBSFN Area constructively interfere, while cells belonging to different MBSFN Areas act as disruptive interference sources. Different MBSFN Areas in the Synchronization Area activate only one multicast video session. 'News' is the video streaming flow considered in our analysis; its Base Layer minimum data rate is 121 Kbps and the data rates for the three Enhancement Layers are 259 Kbps, 372 Kbps and 564 Kbps, respectively [10].

The performance of the proposed heuristic is evaluated by simulations and compared to the performance provided by alternative heuristic approaches. Indeed, we compare the performance of the DMAF algorithm against the static MBSFN Area configuration specified by 3GPP Legacy [18], the SC-PtM [19] scheme, and the SCF algorithm [23]. For a fair comparison between DMAF and SCF, we assume that 60% of RBs are assigned to multicast traffic and the remaining 40% to unicast traffic in each cell. It is worth noting that this assumption has no correlation with the design of DMAF algorithm and has actually no impact on its performance. More in detail, we assume that, when SCF excludes users from the multicast transmission, they are served via unicast links through Inband resources [30]. Resources used for such unicast connections are taken from the set of RBs already assigned to the MBSFN services. Thus, SCF does not waste RBs dedicated to other unicast services. We consider three simulation scenarios:

- Scenario A, where the number of cells is 57, the number of users per cell is fixed to 60, and we vary the bandwidth (3, 5, 10, 15, 20 MHz).
- Scenario B, where the number of cells is fixed to 57, the number of users per cell varies from 60 to 100, and the

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bandwidth of 10 MHz (i.e., 50 RBs)[2].

- Scenario C, where we consider a variable number of cells (19, 26, 36, 46, 57) within the Synchronization Area, a variable number of users per cell (from 60 to 100), and a fixed bandwidth of 10 MHz.

Each simulation run has been repeated several times to get 95% confidence intervals for the most relevant results.

B. Performance Metrics

The behaviors of the described algorithms have been compared in terms of the following performance metrics:

- **Mean Throughput** is the average data rate experienced by users; the higher the throughput the higher the service quality and the 'satisfaction' level of the multicast users.
- **Aggregate Data Rate per cell** is computed as the sum of the data rates experienced by the multicast members in each cell.
- **Spectral Efficiency** is the ratio between the number of bits received by multicast users and the channel bandwidth exploited for the multicast transmission; this metric indicates how efficiently the system resources are exploited during the multicast service provisioning.
- **User Outage** is the percentage of users excluded from the MBSFN delivery.
- **ADR per cell Gain** represents the percentage of improvement in terms of ADR per cell introduced by DMAF with respect to the other compared schemes.
- **Percentage of users receiving the service** measures the percentage of users that receives the content through a single layer or more scalable layers in a Disjoint MBSFN Area or Overlapping MBSFN Area, respectively.

Further considerations on the degree of user satisfaction are available in Subsection V-D.

C. Simulation Results

1) Scenario A: The performance of Scenario A is evaluated by analyzing the mean throughput achieved by multicast users (Fig. 3), the ADR per cell (Fig. 4), the spectral efficiency (Fig. 5), and the percentage of users receiving the service (Fig. 6) when varying the bandwidth. It is worth noticing that the curves for the Legacy and the SC-PtM approaches almost overlap. Indeed, the curve with the mark "o" is relative to the SC-PtM scheme, whereas the mark "x" is related to the Legacy approach. This is due to the fact that both algorithms obtain the same results when performing the Area formation.

[2]Since balancing between unicast and multicast traffic is out of the scope of our proposal, in our simulations we considered a fixed threshold between the two services, i.e., at most 60% of the available RBs for eMBMS and 40% for unicast, as proposed in [23] and [24].

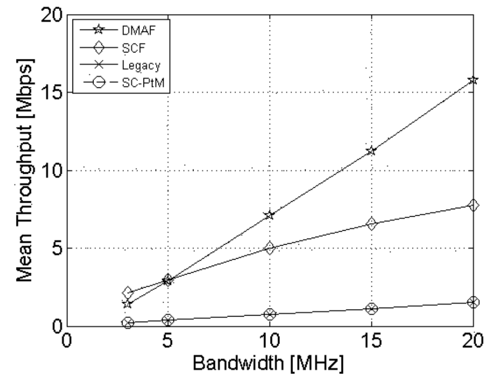

Fig. 3: Case study: scenario A. Mean Throughput.

As expected, both the mean throughput and the ADR per cell increase when increasing the available bandwidth. In Figure 3, DMAF outperforms both the Legacy and SC-PtM schemes, achieving an 8-fold mean throughput improvement with respect to them when the bandwidth is 20 MHz. In lower bandwidth (3-5 MHz) cases, DMAF slightly underperforms with respect to SCF. This small performance degradation is due to the dependence of the created MBSFN Areas on the available RBs. Indeed, if few RBs are available, then DMAF creates only disjoint MBSFN Areas in which the advantages of SVC cannot be exploited and, therefore, the mean throughput suffers from cell-edge user negative effects. Nevertheless, this loss is negligible, because larger bandwidth values are usually exploited for video applications. When increasing the bandwidth (from 10 to 20 MHz), the DMAF mean throughput ranges from 7.11 Mbps to 15.8 Mbps, providing an increasing gain compared to SCF.

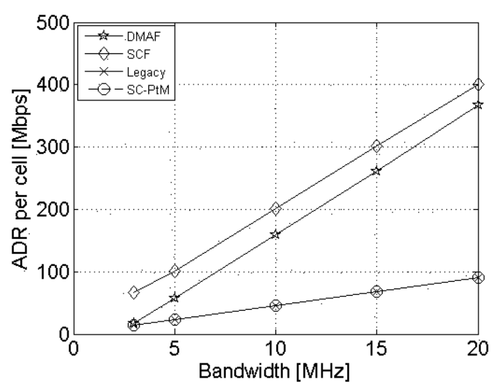

Fig. 4: Case study: scenario A. ADR per cell.

In Figure 4, DMAF provides higher ADR per cell than both the Legacy and SC-PtM schemes, showing an improvement of about 270% and 267%, respectively. This is thanks to the exploitation of SVC; users with good channel conditions can decode both Base and Enhancement Layers. The consequent increase in their data rates leads to such an ADR improvement. SCF achieves a higher ADR than the DMAF because SCF follows an opportunistic policy. This means that users with good channel conditions are favored with respect to those with bad channel conditions. When increasing the bandwidth, the

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percentage of ADR loss of the DMAF algorithm compared to SCF decreases down to 9% for a 20 MHz bandwidth.

Nevertheless, SCF suffers from a high percentage of outage as shown in Table V, whereas DMAF serves all users interested in the eMBMS content. It is worth noticing that the outage of users is considered when a user is served neither by multicast nor by unicast transmissions.

TABLE V: User Outage Analysis.

User Outage (min/avg/max) [%]		
Scenario	**SCF**	**DMAF/Legacy/SC-PtM**
A	15/33/48	0/0/0
B	33/37/40	0/0/0
C	32/40/49	0/0/0

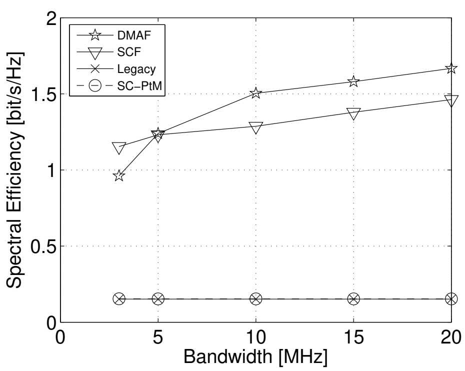

Fig. 5: Case study: scenario A. Spectral Efficiency.

The spectral efficiency values illustrated in Fig. 5 show that both the Legacy and SC-PtM suffer from poor spectral efficiency, which is 0.1523 bps/Hz and 0.1541 bps/Hz, respectively. This trend keeps constant by varying the bandwidth. The proposed DMAF, for a 3 MHz bandwidth, has a 17% loss in spectral efficiency with respect to SCF. Once again, this happens because, with narrow bandwidth, DMAF is not able to exploit the SVC advantages. On the other hand, with a 20 MHz bandwidth, DMAF achieves the highest spectral efficiency of 1.6674 bps/Hz, whereas SCF obtains 1.4624 bps/Hz spectral efficiency.

Fig. 6 depicts the percentage of users receiving the service either through a single flow in a Disjoint MBSFN Area or through more scalable video layers within an Overlapping MBSFN Area, when the bandwidth varies. DMAF performs better with large bandwidths. When the bandwidth is narrow, i.e., 3 or 5 MHz, only 20% and 25% of users receive the Enhancement Layers, respectively. In the case of a 20 MHz bandwidth, the Enhancement Layer can be decoded by 60% of users. In such a case, users receiving only the Base Layer are around 25%. This is the price to pay when adopting DMAF, which is anyhow largely acceptable compared to SCF that suffers from a significant outage probability in similar conditions.

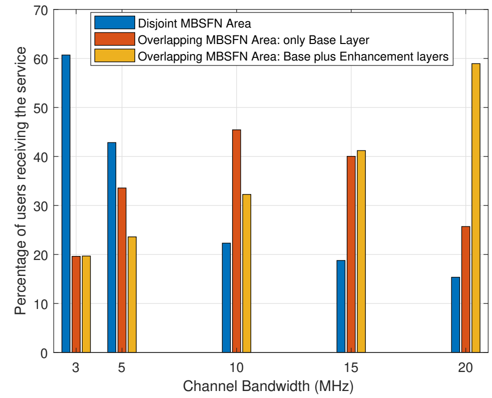

Fig. 6: Case study: scenario A. Percentage of users receiving the service.

2) Scenario B: Scenario B allows measuring the performance when varying the number of users per cell.

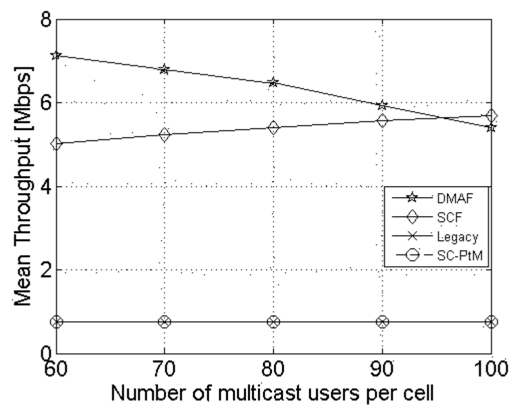

Fig. 7: Case study: scenario B. Mean Throughput.

The user mean throughput is plotted in Fig. 7. As expected, both Legacy and SC-PtM schemes are the worst-performing policies, due to cell-edge users experiencing the lowest CQI. Moreover, when increasing the average number of users per cell, the mean user throughput of these techniques keeps constant to 0.74 Mbps. The mean user throughput of the DMAF algorithm decreases when increasing the number of users due to the higher probability of having users with poor channel conditions. On the contrary, with SCF the mean throughput of MBSFN users increases with the total number of users, thanks to the opportunistic operation of this algorithm, which aims at maximizing the ADR and increasing the MCS level of the MBSFN transmission. It is worth reminding that the mean throughput of served users is computed without considering those users left out of the MBSFN area because of the limited unicast resources. Indeed, SCF shows a high user outage also in this Scenario (Table V).

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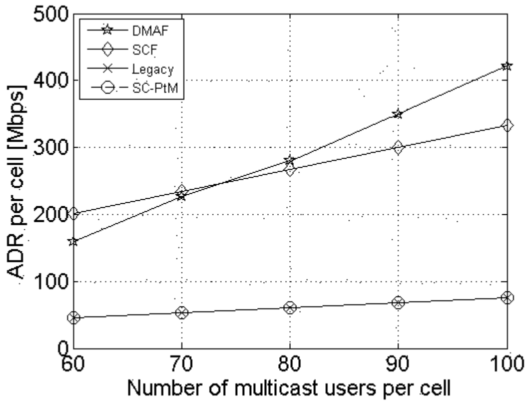

Fig. 8: Case study: scenario B. ADR per cell.

As Fig. 8 shows, the higher the number of users per cell the higher the ADR per cell for all algorithms. The ADR per cell of DMAF ranges from 159.76 Mbps to 421.25 Mbps; the Legacy scheme achieves an ADR per cell between 44.98 Mbps and 74.97 Mbps; for SC-PtM the ADR per cell ranges from 45.33 Mbps to 75.07 Mbps. SCF achieves an ADR lower than DMAF due to the number of outage users, which gets higher because the bandwidth is fixed to 10 MHz.

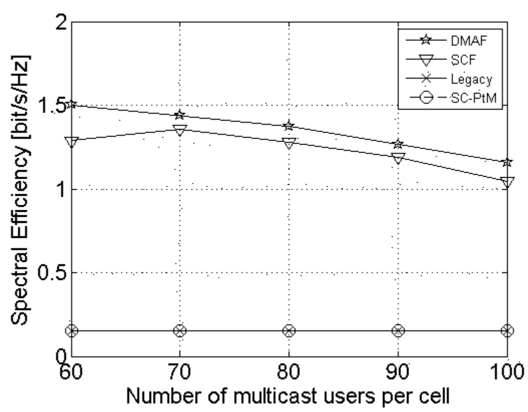

Fig. 9: Case study: scenario B. Spectral Efficiency.

Final comments are on spectral efficiency, plotted in Fig. 9. Also in this scenario, both the Legacy and SC-PtM schemes suffer from poor spectral efficiency (0.1526 bps/Hz and 0.1536 bps/Hz, respectively). Their trends do not change when varying the number of users per cell. DMAF achieves better spectral efficiency than SCF, thus showing to exploits the total bandwidth in a more effective way.

The percentage of users receiving the service through different MBSFN Areas is shown in Fig. 10, for a variable number of users per cell. DMAF performs better when the number of users within the system increases. The percentage of users receiving the Enhancement Layers increases from 32% to 65% under high load conditions. On the other hand, the percentage of users receiving only the Base layer decreases to 20%. The gain introduced by DMAF increases with the numerical difference between users receiving only the Base Layer and users receiving also the set of Enhancement Layers. Finally, when increasing the number of users in the system, few Disjoint MBSFN Areas are created because of users heterogeneity in channel condition and less than 15 % of users receives a single layer rather than more video layers.

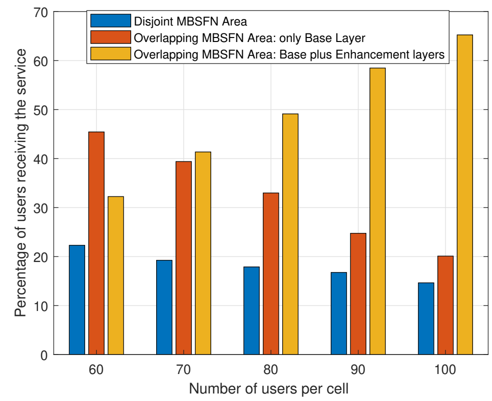

Fig. 10: Case study: scenario B. Percentage of users receiving the service.

3) Scenario C: The objective in this scenario is to assess the performance of the DMAF algorithm when varying both the number of cells over the Synchronization Area and the UE distribution within each cell involved in the MBSFN Transmission. The Synchronization Area is progressively extended from 19 cells to 57 cells, and users are randomly distributed.

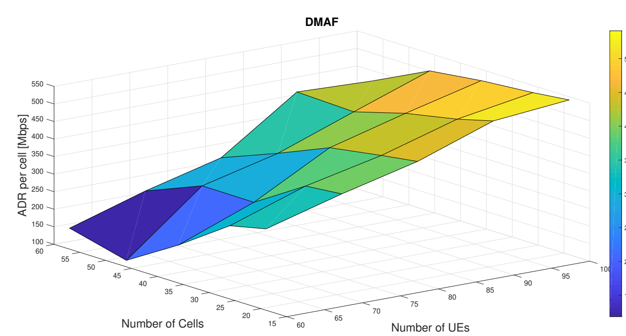

Fig. 11: Case study: scenario C. ADR per cell.

According to Fig. 11, the ADR per cell increases with the number of users per cell. This is due to the cumulative nature of this metric and, hence, to the contribution given by each user. Furthermore, the higher the number of cells in the Synchronization Area the lower the ADR per cell, because the probability of the presence of users with bad channel conditions gets higher. This implies a more robust MBSFN transmission with a consequent reduction of the ADR.

To further investigate the effectiveness of DMAF, in Fig. 12 we present the ADR gain for DMAF versus SCF when fixing the bandwidth to 10 MHz. This further analysis allows observing that DMAF introduces a 70% improvement in the performance in terms of ADR per cell with respect to SCF when increasing the number of users and keeping the number of cells in the Synchronization Area fixed. Furthermore, the

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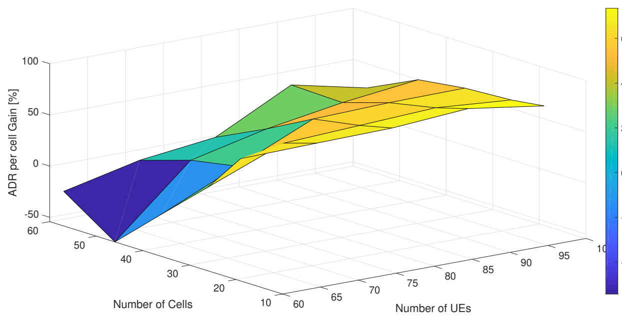

Fig. 12: Case study: scenario C. ADR per cell gain for DMAF versus SCF.

ADR per cell of DMAF decreases when increasing the number of cells, due to the presence of more users with poor channel conditions. Therefore, sometimes a loss in the ADR per cell gain compared to SCF is observed. SCF increases its ADR by delivering the content to the best users via broadcast transmissions. Differently, users with poor channel gain are served via unicast although not all of them can establish a Point-to-Point communication due to the limited availability of RBs. In such a case, SCF achieves up to 49% of user outage (see Table V), whereas DMAF serves 100% of users.

D. Analysis of user satisfaction degree

This subsection provides a more in-depth performance analysis of the considered algorithms by analyzing the user satisfaction degree in a given scenario.
Let us consider a Synchronization Area of 57 cells, each covering 60 users, and a fixed channel bandwidth of 10 MHz. Fig. 13 shows the *Group Satisfaction Index (GSI)* for users supporting a given modulation (i.e., supported MCS). The GSI is the average value of the satisfaction index perceived by all users, where the satisfaction index is defined as the ratio between the assigned data rate and the maximum achievable data rate. The GSI is computed for several groups of users. Specifically, we consider 15 groups, each one including users who experience the same CQI and, hence, supporting the same MCS level.
The Legacy approach delivers the broadcasted content at the most robust modulation supported by users within the area. As it can be seen in Fig. 13, this causes a higher degradation of user satisfaction when increasing the experienced CQI. Therefore, the GSI decreases with the increase in the supported MCS.
The SCF algorithm aims to group users with good channel conditions under the coverage of an MBSFN Area; whereas, users negatively affecting the system ADR (i.e., users with a low MCS) are served through the unicast transmission. This implies high GSI for about 47% of users (i.e., those experiencing a CQI from 9 to 15) and very low GSI for 17 % of unicast users (i.e., those supporting the MCS level up to 8). Furthermore, 36% of users cannot be scheduled due to the lack of radio resources.

As shown in the figure, DMAF foresees that 47% of users with CQI greater than 8 experience a lower GSI w.r.t. SCF; the 20% of users experiencing a CQI from 6 to 8 achieves a notably higher GSI; finally, for the remaining 33% the GSI is, however, greater w.r.t. SCF.
By summing up, DMAF algorithm allows the broadcasted content to be received by 100% of users as opposed to SCF that serves only 64 % of users. To avoid the user outage, DMAF has to pay the price of a reduction in users satisfaction degree with respect to SCF and the Legacy approach when the experienced CQI is higher than 9 and lower than 6, respectively. Nevertheless, differently from the Legacy approach, DMAF proved to be able to improve the service quality perceived by users with good channel conditions.

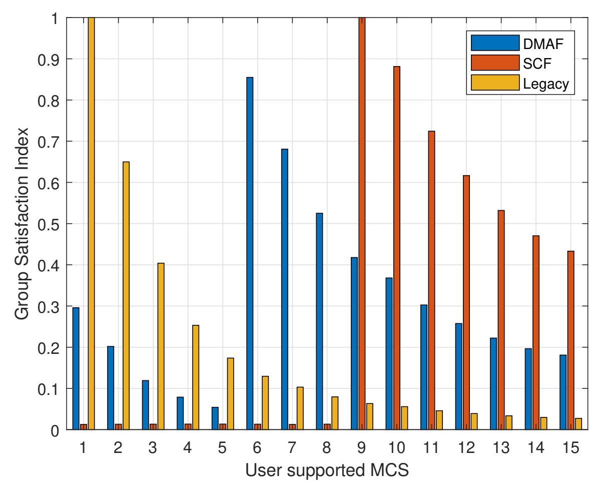

Fig. 13: Group Satisfaction Index.

E. Summary of Performance Results

Table VI summarizes the performance results of DMAF in Scenarios A and B.

TABLE VI: Performance Results of DMAF algorithm

Parameter	Case	DMAF
Mean Throughput (min/avg/max) [Mbps]	A	1.39/7.69/15.89
	B	5.399/6.35/7.12
ADR per cell (min/avg/max) [Mbps]	A	17.52/172.82/368.12
	B	159.76/286.78/421.26
Spectral Efficiency (min/avg/max) [bps/Hz]	A	0.96/1.39/1.67
	B	1.16/1.36/1.50

Finally, Table VII refers to Scenario C and shows Mean Throughput gain, ADR per cell gain, and Spectral Efficiency gain introduced by the proposed DMAF w.r.t. the SCF algorithm.

TABLE VII: Comparison of DMAF and Benefits with respect to SCF.

Parameter	Case	DMAF
Mean Throughput gain [%]	C	-8.7/6.6/42
ADR per cell gain [%]	C	-54/36/73
Spectral Efficiency gain [%]	C	-11.7/1.2/46

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VI. Conclusion

In this paper, we proposed a Dynamic MBSFN Area Formation algorithm for multicast service delivery in 5G NR wireless networks. The proposed DMAF algorithm dynamically creates MBSFN Areas by exploiting the multicast subgrouping approach and the SVC technique. We have shown a performance comparison between the proposed DMAF algorithm and other state-of-the-art algorithms. Results confirm that DMAF *(i)* enhances the overall user performance thanks to the multi-rate approach of subgrouping, *(ii)* improves the perceived video quality for users with higher CQIs, thanks to the SVC technique; *(iii)* increases the ADR by choosing the best MBSFN Area configuration; *(iv)* reduces resource waste, thanks to a proper radio resource allocation, and *(v)* guarantees total coverage by serving 100% of users. As future works, we expect to leverage Device-to-Device (D2D) communications to improve the DMAF algorithm in terms of content delivery time. By introducing high-performing D2D links between UEs, the DMAF algorithm will likely further improve the performance of cell-edge devices and enhance the user mean throughput and the ADR; consequently, the overall performance of MBSFN Areas likely increases.

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