An Adaptive MBSFN Resource Allocation Algorithm for Multicast and Unicast Traffic

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***Abstract*—The need for supporting multimedia streaming services in cellular networks as standardized by 3GPP is expanding rapidly. Evolved Multimedia Broadcast Multicast Service (eMBMS) was initially introduced in Release 9 and following releases have introduced several enhancements. Multimedia Broadcast Multicast Single Frequency Network (MBSFN) is one of the eMBMS enhancements targeting to reduce interference, however, its static parameter configuration yields inefficient resource allocation. Therefore, in this paper, an adaptive demand-driven MBSFN resource allocation algorithm is proposed aiming to efficiently utilize the radio resources. The algorithm flexibly assigns resources to multicast transmissions by varying MBSFN configuration parameters (the number and period of multicast subframes) and provides freed resources to unicast traffic. The proposed algorithm is implemented and evaluated using a Software Defined Radio platform which we made open source. As compared to the fixed MBSFN parameter configuration, our solution showcases an improvement of at least 24% and maximally by 40% in terms of multicast resource efficiency. Also, the total system throughput (multicast and unicast) improves by at least 4% and maximally by 24%.**

***keywords*– LTE, eMBMS, MBSFN, multicast traffic, dynamic resource allocation, unicast traffic, SDR.**

I. Introduction

Efficient resource utilization is of paramount importance in wireless communication systems these days. Ineffective resource allocation severely limits the attainable capacity in a wireless communication system. The situation is even more challenging when both multicast and unicast traffic is to be catered. The huge demand for multimedia streaming services is leading to the congestion of wireless mobile networks as multicast streaming services today are handled by multiple unicast streams [1]. To improve the resource efficiency (i.e. maximizing required versus allocated radio resources) when an increasing number of multimedia streams must be serviced, 3GPP release 9 [2] introduced evolved Multimedia Broadcast Multicast Service (eMBMS), a point-to-multipoint communication architecture for the LTE system. Later, 3GPP Release 11 [3] and 12 [4] came up with multi-frequency deployments and MBMS operation on Demand (MooD), respectively, as further enhancements in terms of performance and flexibility.

Instead of each user receiving a separate multimedia stream from an evolved Node B (eNB), eMBMS allows multiple users to receive the same content, which in turn boosts spectral efficiency. There are two transmission modes of eMBMS: (1) 4G network-based Multimedia Broadcast Multicast Single Frequency Network (MBSFN) and (2) Single Cell Point-To-Multipoint (SC-PTM) [5] with extended 5G network features. The former works by creating groups of multiple cells, known as synchronized MBSFN areas. Within an MBSFN area, the same frequency is used and all User Equipments (UEs) receive same multicast service, hence efficient spectrum utilization. In the latter, SC-PTM transmissions are made on a per-cell basis, without a need for synchronization among different cells. Open and sufficiently stable 5G platforms are not yet available, however, deployment and testing on MBSFN based multicast services have been started recently. Because of this, in this work, we propose, implement and validate an adaptive MBSFN resource allocation algorithm on Software Defined Radio (SDR) based testbed setup.

MBSFN uses a dedicated Multicast Transmission Channel (MTCH) for multicast transmissions. For sharing control information, it uses a Multicast Control Channel (MCCH). One LTE frame consists of 10 subframes (SFs). In MBSFN mode, a maximum number of six SFs (MBSFN Alloc) can be used for multicast transmissions, whereas the remaining four SFs are reserved for unicast transmissions, as well as for control and synchronization information. Fixing the number of multicasting SFs to any value from one to six is not optimal, as the resource allocation will not always be sufficient depending on the actual offered multicast traffic which varies over time. Also, for enhanced flexibility, the frequency of MBSFN frames (MBSFN Period) can be varied. However, owing to the semi-static resource allocation nature of the current eMBMS specification [6], on-going services have to be disrupted if MBSFN parameters are to be varied. To resolve this issue, it is crucial to have a mechanism to vary the MBSFN parameter configuration such that the multicast resource allocation is intelligent and demand-based. This in turn allows for reallocating the unused resources to unicast traffic. In this work, we propose an adaptive MBSFN resource allocation algorithm that optimally selects MBSFN SFs and MBSFN period based on the multicast traffic demand, while giving the unused resources to unicast traffic. We consider the multicast resource allocation decision based on the multicast traffic demand, which is justified because multicast services are intended for a group of users including mission-critical communications.

The following are the main contributions of this paper:

- Experimental analysis of multicast SDR solution with

Table I: Summary of related work.

Reference	Optimization approach	Response metric	SIB2 update period	Compliance to standards	Experimental	Open source
[7]	Adaptive MBSFN Alloc	Multicast resource efficiency	160 ms	✓	×	×
[8]	Shifting TV channels to eMBMS based on popularity	Multicast/broadcast spectrum efficiency	Not mentioned	×	×	×
[9]	Making multicast groups	Multicast spectrum efficiency	Not mentioned	×	×	×
[10]	Multicast groups, Adaptive MBSFN Alloc	Multicast spectrum efficiency	Not mentioned	✓	×	×
[11]	Joint multicast & unicast scheduling, Adaptive MBSFN Alloc	Multicast throughput	Not mentioned	✓	×	×
[12]	Joint multicast & unicast scheduling	Multicast throughput	Not mentioned	✓	×	×
[13]	Scheduling multimedia services via eMBMS & unicast	Multicast/unicast throughput	Not mentioned	✓	×	×
Proposed	Adaptive MBSFN Alloc and MBSFN Period	Multicast throughput Unicast throughput Multicast Resource efficiency	160 ms	✓	✓	✓

fixed MBSFN parameter configurations.

- Introduction of an algorithm for adaptive selection of the number of MBSFN SFs and MBSFN period based on the offered multicast traffic.
- Implementation of modifications in eNB-UE signaling to enable adaptive MBSFN resource allocation. This includes implementing periodic LTE System Information Block (SIB) update feature in MBSFN SDR solution for periodically conveying modified MBSFN parameters to the UE side.
- Experimental evaluation of the proposed solution on top of an SDR-based testbed.
- Open source the developed code to the research community for reproducibility and benchmarking purposes [1].

The remainder of the paper is organized as follows. In Section II, the related work in the domain of broadcast/multicast over cellular networks is presented. Section III presents the system model and problem formulation. The used testbed setup is described in Section IV, followed by a preliminary performance analysis of MBSFN with fixed parameters in Section V. The proposed adaptive MBSFN parameter configuration algorithm is presented in Section VI. The results and analysis are discussed in Section VII, while the conclusion and future directions are drawn in Section VIII.

II. Related Work

The problem of resource allocation in the context of LTE multicasting has been considered in the past and various mechanisms have been proposed. An LTE-Sim based simulation study has been conducted in [7] for dynamic MBSFN SFs allocation based on the linear prediction function of the variable bit rate traffic allocation. In comparison to our proposed adaptive algorithm where we optimally select MBSFN Alloc and MBSFN Period, this work only considers variation in MBSFN Alloc which is less flexible. Also, this work lacks real-time experimental validation and analysis. This is a crucial step to evaluate the performance of the mechanisms in the real world, taking into account any hardware limitations.

ADTVS, an audience-driven live TV scheduling framework has been proposed in [8]. The proposed algorithm in this paper considers audience preferences and available radio resources to switch TV channels to eMBMS, in view of saving precious radio resources. Also, in [9], the authors have proposed an optimal resource allocation mechanism for eMBMS. The mechanism makes groups of multicast UEs based on the channel quality experienced i.e., UEs experiencing poor channel conditions and UEs experiencing better channel conditions are allocated to separate groups. The relationship between UEs' data rate improvement versus spectrum utilization improvement is shown via simulations. The main concern regarding work in [8] and [9] is that the proposed mechanisms are not standard compliant. The unit applied for mapping both eMBMS and unicast traffic is at Physical Resource Blocks (PRBs) level, whereas 3GPP standard [2] specify SFs as a unit for MBSFN. This has been rectified in [10] while reducing computational complexity at the same time.

In [11], a Joint Multicast/Unicast Scheduling (JMUS)

[1] https://gitlab.ilabt.imec.be/mgirmay/adaptive-mbsfn

scheme is presented for delivering multicast services, where dynamic optimization is done on each LTE frame. The scheme selects the number of SFs for multicast transmission, optimal MCS, and also assigns the remaining resources for unicast. However, both proposed exhaustive search and fast search algorithms are iterative and their convergence is slow. This work is missing real-time experimentation to support the findings and is less flexible as it does not consider variation in MBSFN Period, and only relies on MBSFN Alloc. A strategy for making subgroups of multicast users on the basis of their channel correlation matrices has been proposed in [14]. Also, for uplink pilot transmission, a power allocation mechanism to maximize spectrum efficiency between multicast users in a subgroup has been proposed. Although the proposal in [14] is novel, nonetheless, inclusion of adaptiveness in terms of radio resource allocation can help in further optimizing the proposed mechanism. In [15], a mechanism for unicast/broadcast switching for optimal resource allocation is proposed where a threshold is put on number of UEs per BS after which broadcast becomes more advantageous than the unicast as far as resource utilization is concerned. This indeed makes resource allocation efficient, however, the offered multicast/broadcast traffic for these users is not considered so real-time dynamic SF allocation is not supported. A hybrid unicast-multicast utility-based network selection (HUMANS) algorithm is presented in [12]. It schedules eMBMS traffic for UEs with good channel conditions, while the remaining UEs are scheduled to use unicast traffic only. However, this work does not consider efficient multicast resource allocation by varying the number of MBSFN SFs on the basis of offered multicast traffic. In [13], a dynamic radio resource allocation for eMBMS based on RAN congestion is proposed. The idea is to use eMBMS for selected multimedia services whereas using unicast communication for others. However, this work does not consider the joint optimization of MBSFN Alloc and MBSFN Period, and also lacks real-time testbed experimentation and analysis. With an end goal of achieving resource allocation efficiency for mission critical communications, MBSFN, SC-PTM and unicast transmissions have been compared in detail in [16]. For emergencies concerning big events and wide-area layouts, MBSFN is better in terms of performance, whereas, SC-PTM is more suitable for emergencies spanning over a smaller scale. Similarly, for relaying and back-haul scenarios within LTE Advanced, radio resource management w.r.t. MBSFN perspective has been studied in [17].

As summarized in Table I, the current state of the art in this domain only considers variation in MBSFN Alloc for achieving better multicast resource allocation in the context of MBSFN. This restricts the degree of the achieved flexibility as $\mathrm{m_a}$ can only vary from 1 to 6. The joint variation of MBSFN Alloc and MBSFN Period based on the multicast traffic loads is six times more flexible as there are a total of 6 by 6 different possible configurations. To the best of our knowledge, this is the first study in this domain, which considers optimizing MBSFN Alloc and MBSFN Period jointly, based on the multicast traffic loads. Also, the contributions in literature are based on simulations and lack experimental validation. To overcome the shortcoming in the specifications and literature, in this work, we propose and experimentally validate an SDR-based adaptive MBSFN resource allocation algorithm that can dynamically adjust the resource allocation for multicast transmissions to cope with the fluctuations in multicast traffic. Considering the availability of sufficiently stable and open source solutions, a 4G-based MBSFN SDR solution is used in our work. However, the proposed resource allocation scheme can be adapted for 5G-NR. Although there are differences in terms of frame structure and numerologies in 5G-NR, this adaptive resource allocation algorithm can be used for 5G-NR as the MBSFN parameter selection criteria for optimal multicast resource allocation will be the same.

III. System model & Problem Formulation

The system model for adaptive radio resource allocation in context of MBSFN is described in this section. Fig. 1 shows the LTE frame structure in MBSFN mode. As per the standard, MBSFN Alloc, denoted by $\mathrm{m_a}$, defines the number of multicast SFs per frame. Similarly MBSFN Period, denoted as $\mathrm{m_p}$, defines the periodicity of MBSFN frames. Possible values of $\mathrm{m_a}$ and $\mathrm{m_p}$ are $\{1, 2, 3, 4, 5, 6\}$ and $\{1, 2, 4, 8, 16, 32\}$, respectively. A frame is 10 ms in duration and consists of 10 SFs. Within multicast frame, up to six SFs are reserved for MBSFN transmissions whereas the rest of them can be used for unicast and paging information.

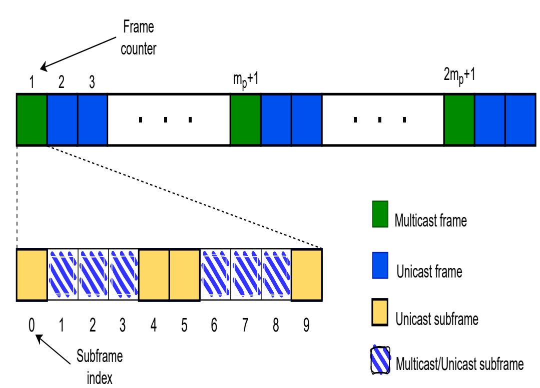


Figure 1: MBSFN frame structure.

For each MBSFN frame, the SF assignment to unicast (u_a) is given as

$$u_a = 10 - m_a. \tag{1}$$

The average effective multicast throughput (T_m) in bits/s, of all multicast UEs and the total unicast effective throughput (T_u) of all the UEs are represented in (2) and (3), respectively.

$$T_m = \frac{1}{m_p} * N_m * 1000 * \frac{m_a}{10}. \tag{2}$$

$$T_u = \frac{1}{m_p} * N_u * 1000 * \frac{10 - m_a}{10} + \frac{m_p - 1}{m_p} * N_u * 1000. \quad (3)$$

where N_m and N_u are the number of correctly received multicast and unicast bits, respectively, in 1 ms for a given bandwidth and a certain Modulation and Coding Scheme (MCS).

Considering the average multicast throughput of each UE T_m and the total unicast throughput of all UEs T_u, the total system throughput (T_s) becomes:

$$T_s = T_u + T_m. \quad (4)$$

The total system throughput T_s can be maximized if efficient resource allocation is used. The Multicast Resource Efficiency (R_m) is defined as:

$$R_m = \frac{Q_m}{C_{\mathrm{m}}(m_{\mathrm{a}}, m_{\mathrm{p}})} * 100\%. \quad (5)$$

where Q_m is the multicast traffic queue length (in bytes) and $C_{\mathrm{m}}(m_{\mathrm{a}}, m_{\mathrm{p}})$ is the capacity of resources allocated to multicast (bytes) per M_{SP}, which is the Multicast Channel (MCH) Scheduling Period and its possible values range from 4 to 1024, in a doubling geometric sequence.

For each possible pair of m_{a} and m_{p}, the capacity of the resources allocated to multicast traffic is calculated as follows:

$$C_{\mathrm{m}}(m_{\mathrm{a}}, m_{\mathrm{p}}) = B_{\mathrm{sf}} * m_{\mathrm{a}} * M_{\mathrm{SP}}/m_{\mathrm{p}}. \quad (6)$$

where the number of bytes in an LTE SF is defined as B_{sf} = (TBS/8) – 6. TBS is the transport block size for a given MCS index. MCS index of 20 is used for the multicast traffic on our SDR-based testbed, which according to Table 7.1.7.1-1 of 3GPP specification [18] corresponds to TBS index of 18, which in turn corresponds to TBS of 19848 bits for 50 $PRBs$ according to Table 7.1.7.2.1-1 of 3GPP specification [18].

Enhancing the multicast resource efficiency means assigning multicast resources based on its traffic demand while leaving the remaining resources for the potential unicast traffic. This, on the other hand, leads to increased T_s. The primary objective here is to maximize R_m keeping the following constraints in consideration:

- In MBSFN, multicast and unicast traffic can not share a single SF. Hence, resources are allocated to multicast and unicast traffic at a resolution of 1 SF.
- SFs are allocated to multicast traffic based on values of m_a and m_p.
- $0 \leq Q_m \leq Q_{\mathrm{max}}$. Where Q_{max} is the possible maximum multicast traffic queue length of the eNB.

Unlike the semi-static MBSFN paramater configuration used in the state of the art, this work aims to formulate a dynamic MBSFN resource allocation that maximizes the multicast resource allocation efficiency. The target is to optimally update multicast resource allocation without disrupting the ongoing multicast services in an MBSFN area.

IV. Testbed Setup

Based on the problem identified in Section III, in this section, we elaborate on how we demonstrate our algorithm. Considering its modular design, we have chosen srsRAN [19], an open-source 4G/5G platform by Software Radio Systems (SRS), as the platform for the development and experimental evaluation of the proposed algorithm. It offers a 4G LTE solution that supports MBSFN in the end-to-end system including UE, eNB, Evolved Packet Core (EPC), and MBMS gateway implementations. srsRAN based end-to-end setup requires a minimum of two Linux host Personal Computers (PCs), one for the UE and one for the eNB, combined with one RF-frontend in each host PC. The EPC and MBMS gateway runs on the same machine as the eNB.

Based on the previous considerations, our indoor testbed setup consists of one eNB host PC and two UE host PCs, as shown in Fig. 2. Each host PC is connected to a Universal Software Radio Peripheral (USRP) B210 board which is used as the RF front end. Our adaptive resource allocation algorithm is implemented on top of srsRAN version 21.04, which is installed on each host PC.

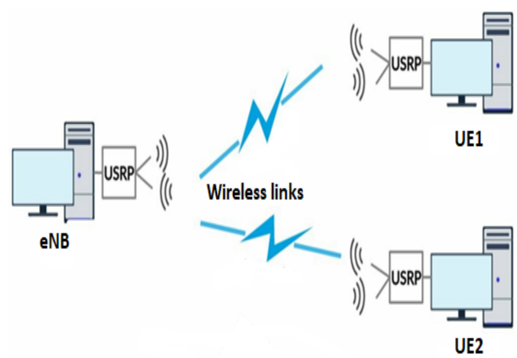


Figure 2: SDR-based experimentation setup.

V. Preliminary Performance Analysis of MBSFN with Fixed Parameter Configuration

In this section, we analyze the performance of the standard MBSFN solution that does not take into account the SF allocation based on the multicast traffic demand. For evaluating the MBSFN performance, User Datagram Protocol (UDP) data traffic has been transmitted using the iperf tool [20] over both unicast and multicast. We have measured the achieved unicast and multicast throughput by manually fixing different values of m_a between 1 and 6 while m_p is set to 1. As discussed above, according to the MBSFN specifications, a maximum of six SFs out of ten that form an LTE frame can be used for multicast services, while the remaining four SFs are used for unicast and also carry synchronization and paging information and, as such, cannot be used for broadcast/multicast services.

Table III shows the throughput results (in Mbps) obtained for different multicast SF configurations. These throughput

Table II: Parameters used for preliminary performance analysis

Parameter	Value
Bandwidth (MHz)	10
Carrier Frequency (MHz)	3550
Traffic Model	UDP
MIMO	NA
MBSFN Service	Enabled
MBSFN Areas	1
MBSFN Frame Allocation Period	1
MBSFN Frame Allocation Offset	0

Table III: Throughout (Mbps) for various SF configurations

m_a	Multicast throughput	Unicast throughput	System throughput
1	1.9	29.5	31.4
2	3.9	28.1	32.0
3	6.0	23.3	29.3
4	8.1	21.0	29.1
5	9.8	16.8	26.6
6	11.5	12.0	23.5

measurements were obtained using parameters listed in Table II. Since the MCS of the multicast service is fixed to 20, we observe a decreasing trend in T_s as more resources are allocated to multicast traffic. It can further be observed that the multicast and unicast throughput vary proportionally with the number of SFs. Allocating more resources to multicast reduces the maximum data rate of a unicast UE while allocating more resources to unicast limits the achievable multicast traffic. Therefore, the cellular network operator must decide how many multicast/unicast SFs should be allocated. The current eMBMS specification uses a semi-static resource allocation mechanism as resources are only modified whenever a new service joins or leaves MBSFN service [6], hence inefficient resource utilization.

VI. Proposed Resource Allocation Solution

To remedy the poor resource efficiency of fixed MBSFN parameter configuration, we propose an adaptive MBSFN parameter configuration algorithm for dynamic resource allocation for multicast and unicast UEs together with implementation of modifications in eNB-UE signaling to enable adaptive MBSFN resource allocation.

A. Adaptive MBSFN Parameter Configuration Algorithm

In this subsection, we propose a rule-based algorithm that assigns m_{a} and m_{p} based on the multicast traffic demand. For each configuration, $C_{\mathrm{m}}(m_{\mathrm{a}}, m_{\mathrm{p}})$ represents the maximum capacity (in bytes) of the multicast resources. Putting all the possible combinations of m_a and m_p in eq. 6, we generate a capacity lookup table that stores all possible values of $C_{\mathrm{m}}(m_{\mathrm{a}}, m_{\mathrm{p}})$ as follows:

$$C_{\mathrm{T}} = \bigcup_{\forall (m_{\mathrm{a}}, m_{\mathrm{p}})} C_{\mathrm{m}}(m_{\mathrm{a}}, m_{\mathrm{p}}). \quad (7)$$

Algorithm 1 shows the procedures used for the optimal resource configuration. The algorithm 1 initializes with minimum multicast resource allocation values for m_{a} and m_{p} i.e. values of 1 and 32, respectively. θ_{m} represents the current queue length of multicast traffic in bytes. Similarly, θ_{m_old} is used for storing previous multicast traffic queue length in the previous scheduling period, with a purpose to compare it with θ_m and check if the traffic has changed. M_{SP} and MCS values are set based on the values reported from the eNB.

The algorithm targets to adapt the values of m_{a} and m_{p} based on the offered multicast traffic queue. As shown in *Step a*, the algorithm works in synchronization with the eNB frame counter (F_{c}). In *Step b* the value of F_{c} is used to control the periodicity of configuration update. As the multicast traffic scheduler of MBSFN updates resource grants every M_{SP}, the adaptive resource allocation solution updates the selected resource allocation configuration periodically after every M_{SP} frames. As indicated in *Step b*, the adaptive configuration is updated if F_{c} % M_{SP} is equal to 0. This shows that potential multicast traffic queue changes are checked periodically with a periodicity of M_{SP} frames.

In *Step c*, θ_{m} and θ_{m_old} are used to determine if the multicast offered traffic load has changed. If a multicast traffic change is observed, new resource allocation configuration is selected in *Step d*. In this step, binary search [21] is used to map the required maximum capacity for the current traffic queue within the possible capacity range values stored in C_{T}. After determining the required maximum capacity, corresponding values of m_{a} and m_{p} are selected using (6). If the traffic queue remains unchanged, there is no need to update the resource allocation and the previous configuration is used. The complexity of the proposed solution is $O(log\ N)$ for an N number of values in C_{T}.

Algorithm 1 Adaptive MBSFN resource allocation

```
Input: Multicast traffic queue in bytes (θm)
Output: Optimal ma, mp configuration
Initialize: ma = 1, mp = 32, θm = 0, θm_old = 0
Set MSP & MCS values based on eNB configuration
Load Capacity lookup table CT based on eq 7
Synchronize with eNB Fc                          ▷ Step a
while true do
    if Fc % MSP = 0 then                         ▷ Step b
        Update θm
        if θm_old ≠ θm then                      ▷ Step c
            Select new configuration             ▷ Step d
            θm_old ←θm
        end if
    end if
end while
```

B. Modifications in eNB-UE Signaling to Enable Adaptive MBSFN Resource Allocation

In LTE, SIBs are used to carry relevant information for the UE. SIBs are generated as Radio Resource Control (RRC) System Information (SI) messages using the Broadcast Control Channel (BCCH) mapped over Down-Link Shared Channel (DL-SCH) and transmitted using the Physical Downlink Shared Channel (PDSCH) at periodic intervals. Specifically, parameters related to multicast transmissions are communicated from eNB to the UE side via SIB2 and SIB13 blocks, which are grouped in one SI message container and it is transmitted every 160 ms. According to the current 3GPP eMBMS specifications, the Multicast Coordination Entity (MCE) determines the number of resources required per MCH only when a new service joins or leaves the MBSFN based MBMS service group [6]. This implies that the resource allocation information in SIB2 and SIB13 is not updated unless a new service joins or leaves the MBMS services group. Similarly, the UE updates the resource allocation provided by a service bearer only when it joins the MBMS service group. In other words, the UE decodes the information in SIB2 and SIB13 when it joins a multicast service and uses the configuration until it leaves the service.

Unlike the semistatic resource allocation in the state of the art, we propose a periodic and adaptive MBSFN resource allocation that is updated based on the real-time traffic demand. To implement this adaptive MBSFN resource allocation, we made changes to the srsRAN SDR source code to enable periodic SIB updates. The modifications are made on both eNB/MCE and UE sides. On the eNB/MCE side, the SIB generation process is modified in such a way that the SIB2 and SIB13 messages are updated in every M_{SP} frames based on our adaptive resource allocation configuration scheme presented in the paper. Similarly, the periodic SIB decoding feature is implemented on the UE side. This feature enables the UE to decode the SIBs every 160 ms and adapts according to the received resource configuration information. The source code of this modified eNB-UE signaling feature, along with the adaptive resource allocation is released as an open source.

VII. Results and Analysis

In this section, results and analysis are presented based on our real measurements in our SDR-based testbed setup. During the performance evaluation, for our chosen LTE configuration (10 MHz of Bandwidth with multicast MCS of 20), we use a fixed unicast offered traffic load of 18 Mbps. This value was used based on the maximum possible unicast throughput obtained. As only multicast traffic load is used in our resource allocation algorithm, this unicast traffic load does not impact the multicast resource configuration decision. We set constant unicast traffic, as we aim to show the impact of our proposed adaptive multicast resource allocation algorithm on the total system throughput and the multicast resource efficiency. Random multicast traffic loads were generated between 0 to 11 Mbps with a granularity of 0.5 Mbps. 11 Mbps is the maximum multicast throughput for the aforementioned parameter configuration. Each randomly selected offered multicast traffic load stays constant for a duration of T seconds where T is a randomly picked integer between 1 and 15. For each randomly selected fixed multicast traffic load, the multicast resource efficiency and the ratio of achieved multicast, unicast and total system throughput to corresponding offered traffic load are computed and stored. For the proposed adaptive MBSFN parameter configuration and each fixed MBSFN parameter configuration scenario, an analysis was made based on 10 runs of an experiment where each run had a run time of 1000 s.

Fig. 3 shows the achieved multicast throughput versus offered multicast traffic load. The fixed configurations shown in (m_a,m_p) format include (3,1), (4,4), (1,32), (5,2) and (6,1). These fixed configurations are selected to include configurations distributed between the lowest (1,32) and highest (6,1) possible resource allocation for multicast traffic. For each of them, the achieved multicast throughput is plotted on the y-axis using solid lines. Dotted lines represent the maximum unicast throughput (T_{u_max}) that we can achieve for each of these fixed configurations as well as for the proposed adaptive solution. The reason for having flat horizontal dotted lines for all the fixed configurations is that the resource allocation remains constant and there is an upper limit that can be achieved in terms of unicast throughput, depending on the configuration. However, for the adaptive scenario, the achieved multicast throughput increases proportionally with the offered multicast traffic, while the maximum unicast throughput (adaptive T_{u_max}) decreases as the resource allocation is dynamically adapted to optimally serve multicast traffic. The multicast throughput, represented by the solid lines, increases up to a certain point after which it remains constant. This is the point where the ratio of actually utilized resources versus the available resources allocated to multicast traffic is approximately one.

A. Throughput versus Traffic Load

Fig. 4 shows the CDF of the achieved throughput versus the offered traffic load for multicast, unicast, and total scenarios. Fig. 4a shows that the best CDF curve is for the adaptive scenario. The achieved multicast throughput versus the offered traffic load ratio is 83% at the median of the CDF. It also shows that as we reduce the resource allocation for multicast traffic for the other fixed MBSFN configurations, the ratio starts getting worse, as clearly illustrated for the (1,32) fixed configuration curve, where the multicast resource allocation is very low. The (1,32) configuration means that there is one MBSFN SF after every 32 frames (320 SFs), thus the ratio is 1/320. Considering another example (red curve), the maximum possible allocation for multicast traffic for 32 frames with (6,1) configuration is 32*6 = 192 SFs every 320 SFs. This shows that the adaptive mechanism is very close to the optimum most of the time.

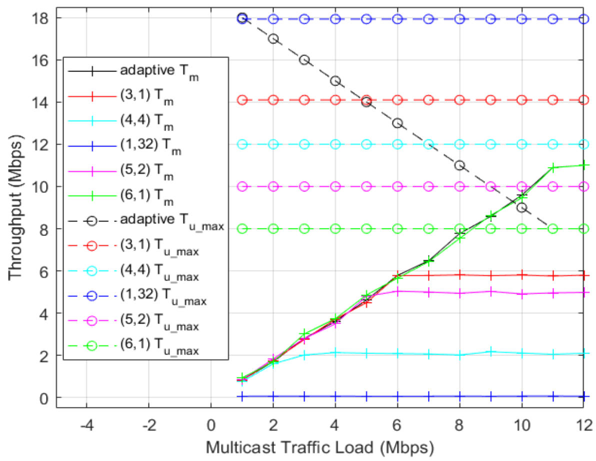
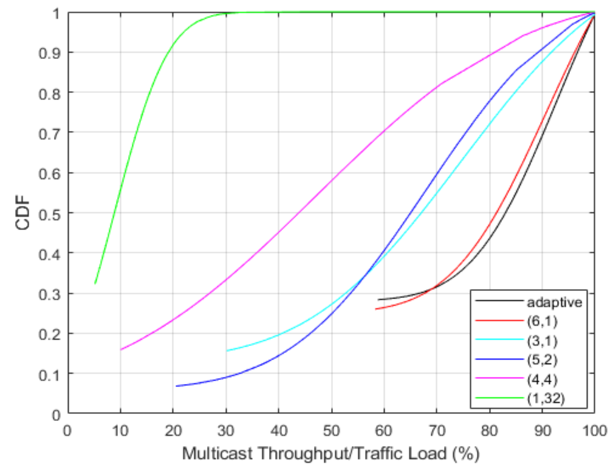


Figure 3: Achieved multicast throughput (solid) & maximum unicast throughput (dotted) versus offered multicast traffic load for fixed configurations and adaptive solution.

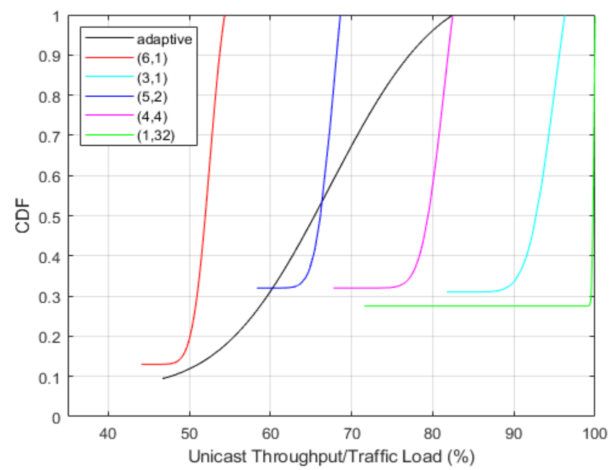
Although the plots for the adaptive and for the (6,1) fixed configuration in Fig. 4 are very close, the underlying difference can be seen in the corresponding plots indicating the achieved unicast throughput versus unicast traffic load, in Fig. 4b. We can see that the adaptive solution has a better ratio because of comparatively better resource assignment to unicast (see red curve versus black curve). This indeed proves that the proposed algorithm not only improves the resource allocation for multicast but at the same time optimizes the unicast resource usage. The curve on the far right in Fig. 4b for (1,32) configuration showcases the best results for achieved unicast throughput versus unicast traffic load. For this configuration, 319 out of 320 SFs are assigned to unicast traffic. The CDF results of total system throughput versus traffic load are shown in Fig. 4c and clearly proves that the proposed algorithm outperforms all the fixed configurations. At the median of CDF, the total system throughput to offered traffic ratio obtained using the proposed adaptive algorithm is around 87%, whereas, it is between 63 and 83% for different fixed configurations used in our experiments.

B. Multicast Resource Efficiency

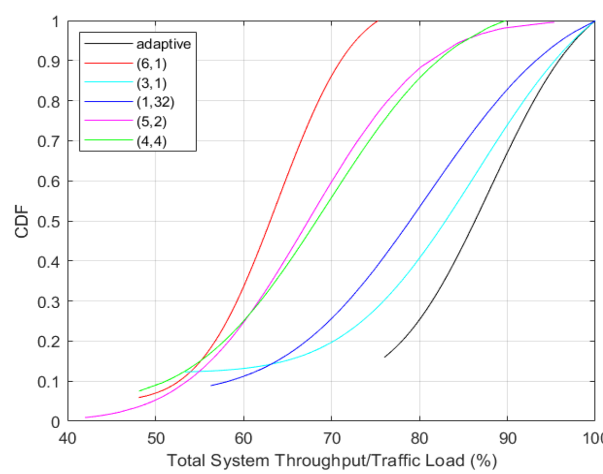
Fig. 5 shows the CDF of multicast resource efficiency. It is a measure to represent the ratio of actually utilized resources versus the available resources allocated to multicast traffic and highlights the usefulness of the proposed adaptive algorithm. For multicast traffic, even though Fig. 3 and Fig. 4a show almost identical behavior for adaptive and (6,1) fixed scenarios, the difference between these two in terms of multicast resource efficiency is clearly illustrated in Fig. 5. At the median of CDF, the multicast resource efficiency for the proposed adaptive algorithm is around 85%, whereas, it is between 45 and 61% for different fixed configurations used in our experiments.



(a) Multicast



(b) Unicast



(c) Total (Multicast + Unicast)

Figure 4: CDF of multicast, unicast, total system throughput vs. corresponding traffic load for fixed configurations and adaptive solution.

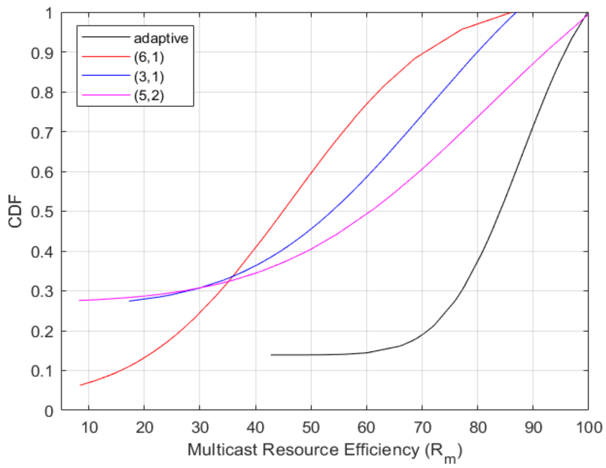


Figure 5: CDF of occupied vs. available multicast resources for various fixed configurations and the adaptive solution.

VIII. Conclusion & Future Directions

In this paper, it is shown how the joint selection of MBSFN configuration parameters (number of MBSFN SFs and MBSFN frame period), improves multicast resource allocation efficiency by at least 24% and maximally by 40% compared to fixed allocation. Also, the total system throughput improves by at least 4% and maximally by 24%. It is experimentally validated that by adapting the configuration parameters in view of optimal support of multicast traffic, there is a huge gain of total system (multicast + unicast) throughput, while the remaining resources (not used for multicast traffic) are more efficiently used for unicast traffic. This resource allocation solution can be adapted for 5G-NR when open and sufficiently stable 5G platforms become available.

The study can be extended by joint adaptive selection of MCS and SFs for multicast. In addition, joint optimization of multicast and unicast, having multiple flows, and prioritizing specific streams are potential future directions. The proposed adaptive resource allocation can also be used to enable MBSFN-based dynamic spectrum sharing between LTE and 5G-NR. Although the proposed algorithm has been validated only for two UEs on top of an experimental platform, we are working on deploying the proposed algorithm of top of a simulator with multiple UEs to address the scalability attribute.

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