Experimental Assessment of New Generation Radio Networks based on Layered Division Multiplexing

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***Abstract*—Despite the recent advances in broadband penetration and accessibility, broadcasting networks continue to be the most efficient way for delivering media content to large areas independently of the user density. Nevertheless, a convergence of broadcasting services into the broadband networks is foreseen. In this context, Layered Division Multiplexing (LDM) allows the joint provision of unicast, multicast, and broadcast services in mobile cells infrastructure. Despite the success of LDM in broadcasting infrastructure, its practical application in Long Term Evolution networks providing Evolved Multimedia Broadcast Multicast Services (LTE eMBMS) and 5G-MBMS is more difficult. In this paper, we experimentally quantify the cell-interference and its impact on the network performance and Quality of Service. Our experiments reveal that the inter-cell interference margin for LTE eMBMS is about 3 dB higher compared to traditional LTE networks. If a layered architecture is incorporated this higher inter-cell interference would cause a reduction of approximately 19% of the Enhanced Layer (Lower Layer) coverage.**

***Index Terms*—Layered Division Multiplexing, RF Interference, Network Optimization, LTE eMBMS, MIMO.**

I. INTRODUCTION

BROADCASTING and wireless network convergence provides a potential solution for the exponential increase of traffic demand, particularly for high quality media content. Despite the advances in broadband access and the increase of bandwidth with the emerging introduction of 5G networks, broadcasting is still the most efficient way for delivering popular or live video in large areas independently of the user density [1].

The latest version of the Advanced Television Systems Committee standard for digital television broadcasting ATSC 3.0 introduced for the first time an all-Internet-Protocol (IP) based transmission. The introduction of IP transmission enables the additional provision of multicast service or cooperative schemes between broadcast and broadband networks [2]. A key enabling technology for sharing resources between services is Layered Division Multiplexing (LDM). The multilayer system allows simultaneously sharing the same spectrum channel by two different services (e.g., unicast and broadcast) [3].

LDM multiplexes the channel in two (or more) layers with different transmission powers and Modulation and Coding Schemes (MCS). It is generally assumed that to the Core Layer is allocated a higher power and the Enhanced Layer is added to the Core Layer with a lower power by $-IL$ (Injection Level). For demodulating the Core Layer, the receiver follows the traditional single-layer signal detection process, and the Enhanced Layer signal is treated as interference. For decoding the Enhanced Layer, the receiver regenerates the Core Layer and subtracts it from the LDM signal [4].

A major difference of LDM with TDM (Time-Division-Multiplexing) and FDM (Frequency-Division-Multiplexing) systems is that the signal power is managed as a resource allocated to each layer for the service multiplexing, and all layers occupy the time and frequency resources simultaneously. It has been theoretically and experimentally demonstrated that LDM achieves a better performance and higher spectral efficiency than TDM and FDM [3], [5]. Authors in [3] proved the feasibility of LDM for ATSC 3.0 infrastructure. In addition, several ATSC 3.0 field trials have demonstrated the higher performance of LDM [6].

In the current LTE network, the Evolved Multimedia Broadcast Multicast Services (LTE eMBMS) are delivered in eMBMS sub-frames in the available Physical Resource Blocks (PRB) in TDM mode [7]. However, the inclusion of LDM in 5G-MBMS [8], [9] enables the provision of unicast, multicast or broadcasting services, multiplexed across the multi-layer architecture.

Different use cases have been proposed for the service configuration for each layer. For instance, the provision of multimedia broadcast or multicast in the Core Layer and unicast in the Enhanced Layer allows decoding the unicast signal by canceling the noise corresponding to the signal of the multimedia content [10], [11]. For this use case the broadcasting/multicasting service is assigned a higher priority. Consequently, to ensure all users receive the broadcasting/multicasting message, some restrictions are imposed in the layered power allocation for guarantee the target datarate considering a certain outage probability [12], [13], [14]. However, this means that for demodulating their unicast content each mobile device must decode the broadcast/multicast signal causing an additional computational requirement, power consumption and a faster battery drain. In a standalone broadcasting system, a use case where the Core Layer deliver a robust high-definition media service to mobile receivers and the Enhanced Layer ultra-high definition content to fixed receivers, address the issue of battery power consumption in

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mobile receivers [7], [4], [1].

Technologies like Tower Overlay in LTE-Advanced+ (LTE-A+) also allow the joint provision of broadcasting media (from a High-Tower High-Power) and unicast services (from a Low-Tower Low-Power) [15]. Because of the wider coverage range of the High-Tower High-Power configuration the intercell interference is decreased compared to the traditional cell configuration in LTE. However, the spectrum efficiency is lower compared to LDM. The tower-overlay configuration in LTE-A+ requires a dedicated broadcast carrier and additional OFDM parameters with longer cyclic prefixes [15], [16].

Simulations of an LTE eMBMS dual-layered network providing broadcasting services, suggest that LDM significantly improves the network performance compared to orthogonal transmission, and that it provides power savings. However, in a real scenario the increased bandwidth available for the broadcast layer does not always outweighs the joint interference caused by the Base Station (BS) self-unicast transmissions and the transmissions from near-by cells (inter-cell interference). Simulations of Further-evolved Multimedia Broadcast Multicast Service (FeMBMS in the 3GPP Release 14), reported a coverage degradation of 18% compared to the target coverage of the traditional broadcasting service [17]. A degradation of the broadcasting service coverage higher than 30% was reported in a field trial in Germany for LTE eMBMS [18].

The provision of joint broadband-broadcasting services in the mobile infrastructure has faced interference issues either for LDM architectures or by inserting the broadcasting content into the available LTE PRBs. We hypothesize that with a higher density of spectrum occupancy related to the broadcasting transmission (independent from the network traffic load), the inter-cell interference might be higher than in the traditional LTE network. As a consequence, a higher cell interference margin has to be considered for the network planning. Opposite to the analysis in [4], we consider that a shorter coverage range for the Enhanced Layer (in LDM architectures) does not solve the coverage issues, due to the fact that with a higher density of Base Stations the inter-cell interference increases.

The novel contributions of this paper are the experimental quantification of the inter-cell interference and the required cell interference margin for the proper modelling and planning of LTE networks providing a joint broadband-broadcast service. The experimental setup allows quantifying the maximum level of intercell interference caused by the additional broadcasting traffic in the mobile infrastructure. A method for the optimization of layered mobile networks, considering a multi-objective approach for balancing the trade-off between performance indicators of both layers is also proposed. Based on the experimental results, we model and optimize an LTE eMBMS network, considering an LDM configuration for the provision of unicast/broadcast or unicast/multicast services.

The outline of this paper is as follows. In Section II we present the research method, including the experimental setup for emulating the interference in an LTE eMBMS network and the network planning and optimization considering different LDM configurations. In Section III we present our research findings. Finally, the research conclusions and future work are presented in Section IV.

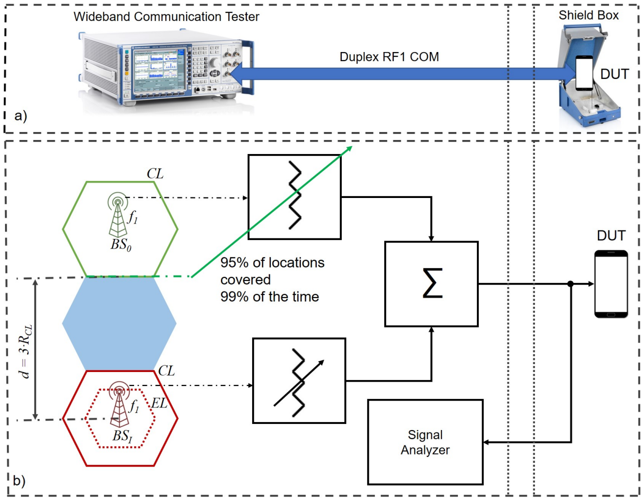


Fig. 1. Experimental setup for determining the cell-interference margin a) testbed hardware, and b) logical diagram (DUT: Device Under Test, BS_0: Base Station providing service, BS_I: nearest Base Station causing interference, CL: Core Layer coverage, EL: Enhanced Layer coverage, d: distance, R_{CL}: Coverage range for the Core Layer, f_1: Cell frequency, ATT_0 and ATT_I: path signal level control, and Σ: bidirectional adder).

II. METHOD

A. Emulation of Inter-cell interference in the mobile network

In a real mobile network scenario, several variables outside our control intervene (e.g., load traffic and environmental conditions) and might influence the outcome of experiments [19]. Therefore we emulate in an experimental testbed the conditions of a realistic mobile network scenario. In a joint broadband-broadcast network, beside the data traffic and signalization there is an additional spectrum occupancy by the broadcasting service independent of the traffic load. The goal of the experiment is quantifying the broadcasting service impact on the intercell-interference and determining an appropriate cell interference margin for a convergent broadband-broadcast network. For the network emulation, only part of the model is performed by a part of the real system [19]. In this experiment, we modeled the signal level conditions for a dual-layered LTE network at the cell edge and mimic the effect of broadcasting spectrum occupancy by the insertion of a media streaming in all the PRBs dedicated to eMBMS. Considering the emulation limitations compared to the real system and that LDM has a higher spectral efficiency than TDM/FDM, the cell-interference margin (output) from this experiment can be considered as an upper limit for further network planning and optimization in dual-layered mobile networks.

Fig. 1 shows a) the testbed hardware and b) the logical diagram for the emulation of the joint broadband-broadcasting network for determining a realistic cell interference.

In the experimental setup the Wideband Communication Tester (in Fig. 1a) allows emulating the LTE cell infrastructure, settling a duplex communication with the Device Under Test (DUT) and measuring different communication parameters (e.g., Bit Error Rate, Signal-to-Interference-to-Noise-Ratio (SINR) and throughput) [20]. The DUT is a real

TABLE I
LINK BUDGET PARAMETERS

Parameter	LTE eMBMS	Unit
Frequency (max)	803	MHz
Bandwidth	20	MHz
Radiated Power	61	dBm
Enhanced Layer Injection Level	-7 to -4	dB
Core Layer SNR		
1/3 QPSK	1.0 to 2.2	dB
Enhanced Layer SNR		
4/5 16-QAM	13.5 to 15.8	dB
2/3 64-QAM	17.0 to 19.3	dB
4/5 64-QAM	19.5 to 21.8	dB
Shadow Margin	10.1	dB
Building Penetration Losses	10.2	dB
Fading Margin	7.4	dB
Receiver Gain	0|6	dB
Receiver Noise	6	dB

commercial user device that is placed inside a shield-box for avoiding external interference and minimizing the signal reflections from external objects [21].

Fig. 1b shows the logical diagram of the experimental setup. By means of the Wideband Communication Tester, two base stations are emulated. BS_0 corresponds to the cell that is providing coverage to the DUT. BS_I is the base station corresponding to the nearest cell in the infrastructure that is reusing the same frequency as BS_0 (f_1 in Fig. 1b).

We set the signal level (ATT_0 in Fig. 1) assuming the DUT is located at BS_0 coverage edge. The signal level set at BS_0 corresponds to the cell edge for the mobile data service (Core Layer) guaranteeing an indoor coverage at 95% of locations 99% of the time. The signal level set for the experiment is defined by means of equation 1:

$$S_{ce} = EIRP_{CL} – PL_{max} \tag{1}$$

where S_{ce} [dBm] is the signal strength at the cell edge (equivalent signal level in dBm at the receiver antenna input considering a height of 1.5 m) for the defined coverage requirements, the $EIRP_{CL}$ [dBm] is the radiated signal level for the Core Layer (providing data service), and PL_{max} [dB] is the maximum path loss that the signal can experience for the network coverage requirements. PL_{max} depend on the link budget parameters according to the technology specifications and the scenario characteristics. The key link budget parameters for LTE eMBMS in the considered scenario are defined in Table I.

The link budget allows quantifying the maximum allowable path loss for each service. We consider the lower allocated band for mobile services at the UHF band in Belgium. The maximum radiated power already includes the output power, feeder losses and antenna gain for a macrocell BS [22]. For the LDM configuration modeling we consider four different injection levels in the range from -7 to -4 dB, referenced to the Core Layer radiated power [7], [4]. For each injection level and MCS configuration a different pair of minimum SNR is required for decoding each layer [7], [4]. In the LTE-based infrastructure the antenna orientation is not accounted for. For this reason we considered for the Enhanced Layer service a receiver with an omnidirectional antenna (6 dBi absolute gain in the horizontal plane and including feeder losses) and no gain for the mobile device (Core Layer service).

The coverage of each service (coverage range) r [km] is defined by the maximum allowable path loss PL_{max} [dB], the environmental propagation function $g(\cdot)$, and a certain margin to account for the signal fading L_{fd} [dB] and shadowing L_{sw} [dB] [23]. Equation 2 defines the coverage range as a function of the maximum allowable path loss:

$$R = g^{-1}\left[(PL_{max} - L_{fd} - L_{sw})\,|f, h_{tx}, h_{rx}\right] \tag{2}$$

where f is the frequency [MHz], h_{tx} and h_{rx} are the height [m] above the terrain of the transmitter and receiver, respectively and $g(\cdot)$ is the propagation path loss model. A customized one-slope path loss model for Ghent propagation conditions and a similar setup of antennas heights is defined in [23] as a function of the distance r:

$$g(r) = 86.77 + 23.4 \cdot log(r/0.1) + C_f \tag{3}$$

As the original one-slope path loss model was developed based on measurements at a frequency 200 MHz lower than for this application an additional attenuation factor based on the frequency (C_f) [dB] is applied [23]. This path loss model is based on a large-scale measurement campaign for this scenario and the same frequency band, having a higher accuracy than a generic path loss model.

For accounting for the effect of interference from other cells, we consider that the network frequency distribution is either a 1*3*3 (each adjacent cell uses a different frequency sub-band) or 1/3 frequency band per sector. For this frequency allocation the closest cell transmitting at the same frequency is located at $3 \cdot R_{CL}$ (BS_I in Fig. 1b). The mean path loss experienced by the interference signal from BS_I to the coverage edge of BS_0 is defined by $g(3 \cdot R_{CL})$.

BS_I signal is configured for LTE eMBMS, providing both unicast and broadcast services with a full occupancy of the LTE PRBs. The signal level from BS_I is set by ATT_I and internally added (by Σ) in the Wideband Communication Tester to the signal from BS_0 (in Fig. 1b). The initial conditions of the experiment are defined, considering no interference between cells. For the initial conditions, only the SNR is accounted for, and it is verified that the Data-Block-Error-Rate (DBLER) of the DUT is lower than 1% during 99% of the time as for these conditions the throughput degradation is negligible [24], [25]. The measurement is also performed by the Wideband Communication Tester. This verification of the quality of service, guarantees that the assumed settings match with the coverage requirements at BS_0's cell edge as defined for the emulation. The signal from BS_I is increased progressively (by ATT_I in Fig. 1) until the Data-Block-Error-Rate is higher than 10% for which the throughput degradation is lower than 25% of the maximum effective throughput [24], [25]. For these conditions, the Cell-Interference-Margin CIM [dB] can be accounted for as:

$$CIM = SINR_{99}(DBLER_{10}) – SNR_0 \tag{4}$$

where $SINR_{99}$ [dB] is the 99^{th} percentile of the SINR for which, the data block error rate recorded is higher than 10%, and SNR_0 [dB] is the signal-to-noise-ratio for the initial noise condition (without cell interference) for each modulation and coding scheme.

B. Multilayered Network Planning and Optimization

For analyzing the impact of the experimentally quantified CIM in mobile network performance, three Key Performance Indicators (KPI) are assessed for a mobile network scenario in Ghent, Belgium (i.e., network power consumption, percentage of users and area covered). In our application the broadcasting signal is intended for fixed receivers only and not for providing mobile media content. We consider the power consumption as a critical parameter. For this reason, we assume the Core Layer is delivering a typical data service (unicast) to mobile users (e.g, smartphones) for a total traffic demand of 220 Mbps, and the Enhanced Layer is delivering a broadcasting media service based on an outdoor-over-the-roof antenna configuration (according to the specifications in Table I). A drawback is that it is required that the fixed receivers to demodulate other users' signals to extract the broadcast messages [10].

For the network simulation at the physical layer level, we use the network optimization tool GRAND (Green Radio Access Network Design) [26], [27]. The GRAND heuristic algorithm allows a dynamic wireless network modelling and optimization based on the network traffic demand (capacity-based heuristic algorithm). However, this software and its network optimization algorithm do not provide support for multilayered communications. For this reason we modified the GRAND heuristic algorithm for splitting the physical communication into two layers.

The objectives of the GRAND algorithm considered for our network are the network power consumption and coverage in terms of both area covered and percentage of users covered. For the network modelling and optimization, the evaluated variables are the users' geolocation and traffic distribution in the map. The geolocation distribution and traffic per user distribution is randomly generated by the software based on the input parameters density of users and maximum traffic per user.

Algorithm 1 shows the dual-layer LTE eMBMS network modelling and optimization algorithm. As the algorithm is capacity-based, different parameters related to the network capacity and user demand are required as inputs. Based on these parameters the Green-field-network planning (initial network configuration) is generated. This initial setup also includes different user and traffic distributions for the defined number of simulations. From the initial setup the algorithm analyzes the optimal user-to-BS connections for minimizing the network power consumption and maximizing the coverage objectives. This step is repeated for each simulation (considering the different network variables) and the progressive average of each objective is found. More details on the algorithm inputs, Green-field-network planning, required number of simulations and network dynamic optimization are provided in the following subsections.

1) Inputs: The algorithm receives as inputs the users density, the traffic per user for either data service demand o VoLTE, and the BSs configuration, including the link budget parameters (same as in Table I). In addition, the settings for the LDM downlink including the MCS for the Enhanced Layer, the injection level, the cell interference protection margin (obtained from the LTE eMBMS experimental emulation from subsection II-A) and the specific SNR for the Enhanced Layer are other inputs.

Algorithm 1 Network Optimization Algorithm

```
Input: users, traffic, BSs, LDM_config;
1:  Generate (Green-Field_Network);
2:  while $Sim < Max\_Sim$
3:    if Data $(u_i)$ ==TRUE
4:      for $u_i <$ users
5:        for $BS_j < BSs$
6:            Set_Radiated_Power $(u_i, BS_j)$;
7:            if Network_PC$(u_i, BS_j)$ < current_NPC
8:              if Active $(BS_j)$ && Bitrate $(BS_j)$
9:                connect;
10:             end if;
11:           end if;
12:           if unconnected
13:             set_active_BS (best_NPC$_i$);
14:             connect;
15:             load_balance;
16:           end if;
17:       end for;
18:     end for;
19:   end if;
20:   Enhanced_Layer_Coverage_Grid $(BS_a)$
21:   for $u_i <$ users
22:     while connected$_{CL}(u_i)$ && $(SINR_{EL} > SINR_0)$
23:       BS_Radiated_Power $--$;
24:     end while;
25:   end for;
26:   Generate (LDM_Network_Solution);
27: end while;
Output:
28: LDM_Network_Solutions;
```

2) Green-field Network Planning: First, based on the input parameters and constraints, the algorithm generates a green-field network model with the initial settings and locations of the BSs (line 1 in Algorithm 1) This initial planning takes into account the minimum number of BSs that satisfy the Core Layer coverage requirements plus a 10% additional infrastructure as a margin for avoiding congestion. The users are randomly and uniformly distributed over the whole area [26], [28].

3) Number of Simulations: The algorithm runs for a total number of simulations (Max_Sim in line 2, Algorithm 1). The number of simulations is defined by the progressive average of the network percentage of users covered and network power consumption. We consider that if the progressive average of any KPI has a standard deviation higher than 2%, the number of simulations is not high enough.

4) Dynamic Optimization: The algorithm verifies if there is a traffic demand from each unicast user u_i. For each user u_i demanding traffic in the area, the algorithm tries to find the connection to the BS_j that best suits the network coverage objective [26]. For the BS_j's Core Layer maximum coverage range, the algorithm seeks if the u_i is located in its range (line

TABLE II
LTE eMBMS BS Power Consumption

Parameter	Value	Unit
LTE eMBMS Gateway (max) P_G [32]	20	W
Optical backhaul P_{obh} [33]	19.5	W
Digital Signal Processing (max) P_{DSP} [34]	100	W
Rectifier P_{rect} [34]	60	W
Transceiver (max) P_{TR} [34]	100	W
Amplifier efficiency η_{amp}	0.15	-

4 to 6 in Algorithm 1) [26], [28]. The power consumption is minimized by applying two strategies. First, the number of active BSs is minimized. For this, a new BS is activated if the total network power consumption [29], [30]) is reduced by connecting users to this new active BS (line 7 to 11 in Algorithm 1) or if the coverage requirement is not satisfied (some users are not connected, see line 12 to 14). After activating a new BS, the algorithm verifies if by switching to this new active BS already connected users it is possible to improve the load balance (line 15 in Algorithm 1).

The second strategy for reducing power consumption is reducing the radiated power. However, there is a trade-off with the Enhanced Layer coverage. For assessing the Enhanced Layer coverage the algorithm generates a footprint of the radiated levels for this layer (line 20 in Algorithm Algorithm 1) and verify that a reduction in radiated power still improves the SINR for the Enhanced Layer ($SINR_{EL}$). It is also verified that already connected users to the Core Layer do not lose coverage (line 21 to 25 in Algorithm 1). Finally, for each simulation Sim, the algorithm generates the dual-layer network solution. The algorithm output includes all users' connection set in the Core Layer, the Enhanced Layer footprint defining the broadcasting media service coverage, the power consumption per BS, density of active BSs, and delivered throughput by the network.

5) LDM Network Power Consumption: The power consumption of LTE BSs has been widely investigated [31], [26], [22]. Next to the fixed power consumption contributing to the BS idle power consumption, the total radiated power is affected by the multilayer configuration and the radiated power dependent on the data service optimization by the BS. The total power consumption PC_n of the LTE eMBMS network is calculated as follows:

$$\begin{aligned} PC_n\left(t\right) = P_G + \textstyle\sum_{j=1}^{k} \{\, P_{obh} + n_s \cdot [P_{rect} + \\ + P_{DSPj}\left(t\right) + n_{tx} \cdot \left(P_{TRj}\left(t\right) + \frac{P_{AMPj}(t)}{\eta_{amp}} \right)] \end{aligned} \tag{5}$$

where t is the time stamp analyzed, j is the index of the LTE eMBMS BS, k is the total number of BSs, n_s is the number of sectors, n_{tx} is the number of transmitters, and P_{AMPj} [W] is the output power at BS_j's amplifier. The power consumption of the BS components (from equation 5) are defined in Table II.

The power consumption of the LTE eMBMS gateway, Digital Signal Processing engine, Transceiver and Amplifier are dependent of the BS status at a certain time stamp ($active$ or $idle$) and are denoted by the BS index j in equation 5. The power consumption of the bidirectional amplifier P_{AMP} is also dependent on the radiated power of the BS at each time stamp. The radiated power is accounted for both the Enhanced Layer and Core Layer and affects the power consumption of the amplifier by a factor η_{amp}, corresponding to the amplifier efficiency.

C. MIMO Diversity for Improving the Enhanced Layer Coverage in Data Applications

For multimedia broadcasting applications, the Enhanced Layer coverage might be improved by synchronizing the transmission, in a similar way to the Single Frequency Network (SFN) architecture. If the service delivered by the Enhanced Layer is synchronized, the interference caused by the cells using the same frequency is reduced [7]. For multicast or even data applications in the Enhanced Layer, this solution is not possible. Although MIMO diversity and multiplexing capabilities are included in the Release 16 of the 3GPPP LTE Technical Report TR 36.776 for both the eNodeB and user devices [35], LDM is not standardized for the provision of eMBMS [36], [7]. However, in [36], authors demonstrated the feasibility of MIMO multiplexing for increasing bandwidth in future LDM-based 5G MBMS networks, delivering point-to-multipoint communications. Nevertheless, the capability of MIMO diversity for enhancing the coverage for multicast and data services delivered through the Enhanced Layer has to be investigated.

The total diversity gain depends on several factors, i.e., the number of receiver antennas for correlating received symbols, antennas beam angle, elevation, the frequency diversity and MIMO diversity. Here, we investigate the capability of MIMO diversity for improving the Enhanced Layer coverage for data applications. Theoretically, for the LTE infrastructure, the maximum gain by a MIMO configuration G_{Mmax} [dB] of N_t transmitting antennas and N_r receiving antennas is defined in equation 6 [37].

$$G_{Mmax} = 10{\cdot}log(N_t{\cdot}N_r) \tag{6}$$

However, in real applications, the gain by a MIMO configuration depends on the scenario, system configuration, and other environmental factors. Authors in [38] found that for any given configuration and a realistic propagation channel, the relative MIMO gain (compared to the equivalent SISO configuration) is correlated to the distance between the LTE BS and the receiver. Particularly, for the higher MCS (64-QAM configurations), the relative MIMO gain trends to G_{Mmax} up to a distance of approximately 200 m and exponentially decreases to a minimum gain from 1000 m. As our research aim is finding the effective coverage for the Enhanced Layer, we consider the minimum relative MIMO gain as defined by [38] for the cell coverage edge, i.e., 5.8 dB for MIMO 2x2 and 9.5 dB for MIMO 4x4.

III. RESULTS

A. Experimental Assessment of the Cell Interference Margin

Fig. 2 shows the minimum required SINR for achieving an effective throughput equivalent to the 10% DBLER for unicast users.

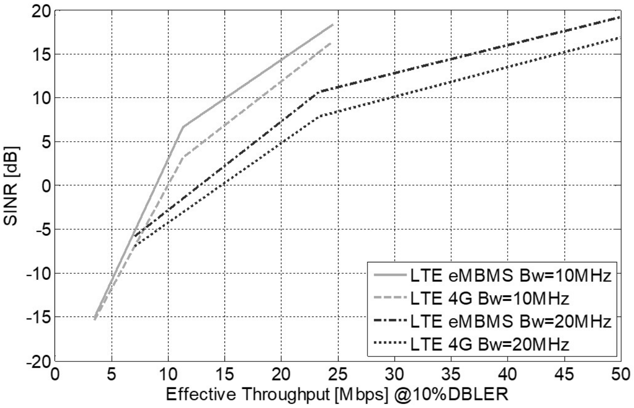


Fig. 2. Minimum required SINR for an effective throughput equivalent to the 10% DBLER for LTE eMBMS and LTE 4G (compliant to 3GPP LTE Release 12 and without multimedia broadcasting capability) with 10 MHz and 20MHz bandwidth.

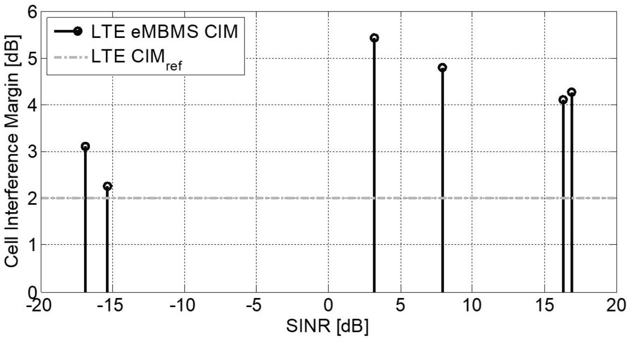


Fig. 3. Inter-Cell Interference Margin (SINR: Signal-to-Interference-to-Noise-Ratio).

The obtained SINR corresponds to the samples 99^{th} percentile in the time domain. For the lower MCS (implementing QPSK mapping with a throughput of 3.953 Mbps and 7.884 Mbps, at 10 MHz and 20 MHz bandwidth respectively) and a maximum throughput degradation equivalent to the 10% DBLER, the SINR difference between LTE and LTE eMBMS is lower than the standard deviation (1 dB). However, for higher datarates the SINR difference between LTE and LTE eMBMS increases up to a maximum of 3.4 dB. This means a higher interference occurs in the LTE eMBMS network. In this experiment we do not emulate the effect of adjacent cell interference. For this reason a slightly higher interference might be expected for lower bandwidths, because of a higher fragmentation of the spectrum.

Fig. 3 shows the inter-cell interference margin for the LTE eMBMS network. A dashed line shows the Cell Interference Margin for a traditional LTE 4G network (without multimedia broadcasting capability).

For the lower modulation schemes (QPSK) there is not a significant variation of the inter-cell interference (below 1.1 dB). However, for higher MCS the inter-cell interference is in the range from 4.1 to 5.4 dB. This margin is at least 2.1 dB higher than in a typical LTE network. The higher inter-cell interference perceived in our experiments is caused by a higher spectrum occupancy, due to a higher utilization of the PRBs (for providing broadcasting services) compared to a traditional LTE network.

This additional interference caused by the broadcasting service might have a significant impact for multilayered network planning. It is important to remark that LDM performs better that TDM and FDM [5] if the cell coverage range is large enough, (e,g., about 15 km in typical ATSC 3.0 application cases) [7], and the inter-cell interference is negligible. Our experiments show that because of the smaller cell coverage range of typical LTE mobile service applications (i.e., <2 km), inter-cell interference plays an additional role in the LTE eMBMS network performance. This additional interference in practical applications might cause a smaller cell coverage range, and a decrease in the percentage of coverage, either spatial, temporal or both. For LDM practical applications, this effect might be particularly noticeable for the Enhanced Layer with the less robust modulation and coding scheme.

B. Impact of the Cell Interference on Network Performance

1) Network Coverage: A higher Cell Interference Margin does not necessarily decrease the network coverage. The LTE network could be reorganized with a larger density of BSs and lower radiated power for minimizing the interference and increase the coverage in a traditional LTE network. However, this is not the case of the LTE eMBMS network with a multilayer architecture. A higher density of BSs might benefit the service in the Core Layer but at a cost of lower performance in the Enhanced Layer due too poor signal levels.

For the network design analyzed in our scenario the percentage of users covered by the Core Layer is on average 98% with a standard deviation of 0.5% considering all network configurations. The QoS as a function of the average demanded bitrate to effective served datarate ratio is 99.1% with a standard deviation of less than 0.1%, considering all the network configurations. However, for the Enhanced Layer, the percentage of area covered by the service is significantly impacted by the inter-cell interference.

2) Enhanced Layer Service Coverage: Fig. 4 shows the percentage of area covered by the Enhanced Layer service considering the Cell Interference Margin from a traditional LTE infrastructure (2 dB) and the experimental CIM obtained from our measurements in Section III-A (4.3 dB to 4.8 dB depending on the layers' MCS array).

Considering the typical cell interference margin of an LTE infrastructure (2 dB) the Enhanced Layer coverage should be near 95% for the LDM configurations requiring a SNR up to 18 dB. However, as demonstrated by field trials the real coverage can be as low as 70% due to interference [18]. The typical LTE inter-cell interference margin is not realistic for LTE eMBMS. Although longer cyclic prefixes can increase the area covered up to 95%, for the higher MCSs the coverage probability is roughly increased to 90% [4], and a more discrete improvement should be expected in a multiplayer architecture.

Considering the cell interference margin from our experimental assessment (4.3 dB to 4.8 dB) a more realistic network modeling is obtained. The impact on the Enhanced Layer area

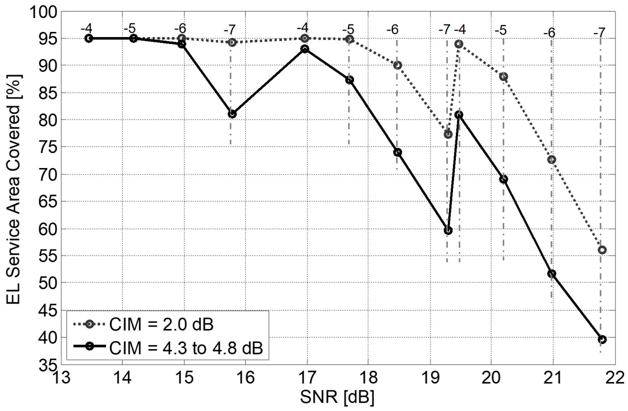


Fig. 4. Enhanced Layer (EL) service percentage of coverage as a function of the minimum required SNR for a certain LDM configuration. Markers denote the Injection Level [dB].

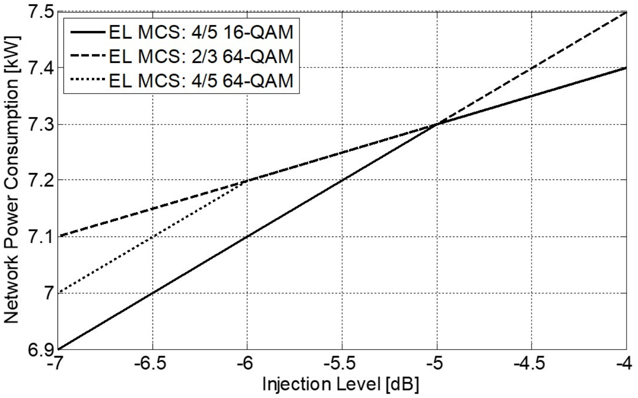


Fig. 5. Network Power Consumption as a function of the Injection Level.

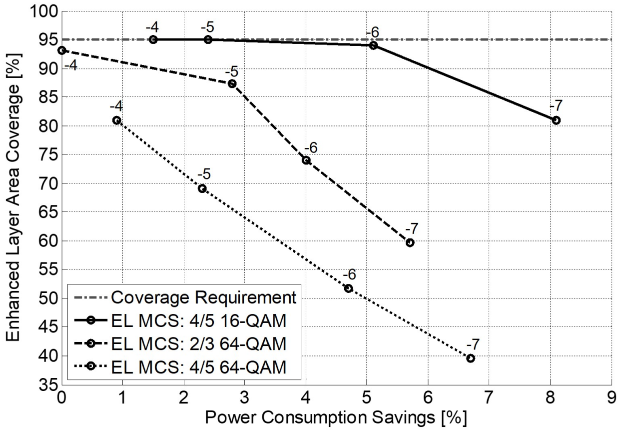


Fig. 6. Enhanced Layer Coverage as a function of the normalized network power consumption savings of the LTE eMBMS network. Markers denote the Injectiopn Level [dB].

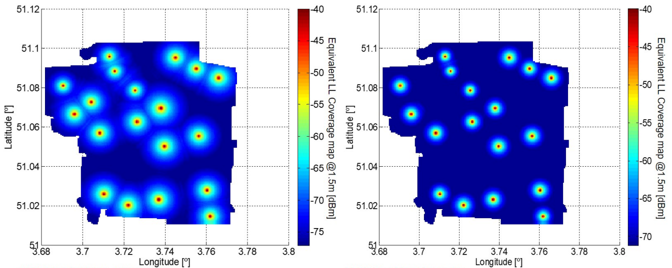
coverage compared to a 2 dB CIM can be as high as 20.9%. For the LDM configurations with the lower MCS (Enhanced Layer MCS 4/5 16-QAM or 2/3 64-QAM) requiring a SNR lower than 17 dB, the achieved coverage is around 95%. Notice that a maximum variation of 41% might be caused by the injection level for the higher MCS. For a SNR requirement from (19.46 dB to 21.79 dB) corresponding to the higher MCS (4/5 64-QAM) in the Enhanced Layer the percentage of area covered is 37.4% to 82.2% depending on the layer injection level. As a consequence, the Enhanced Layer service coverage can only be realistically satisfied by using the lower MCS and an injection level higher than -5 dB. For this MCS the effective throughput is 27.5% lower than for the higher MCS analyzed. A higher radiated level does not contribute to improve current results, but worsening as consequence of a higher inter-cell interference. For achieving the maximum throughput and satisfying the coverage requirements with the higher MCS it is required to compensate the coverage losses by a Single-Frequency-Network for the Enhanced Layer service (broadcasting service).

3) Network Power Consumption: For the Core Layer coverage the injection level has no significant impact as this layer is referenced to the maximum signal level radiated by a macrocell BS with a small variation caused by the distribution of users in the area (difference lower than 1 dB). However, the injection level plays a major role in the network power consumption. Fig. 5 shows the network power consumption as a function of the injection level for different MCSs in the Enhanced Layer.

The MCS configuration of the Enhanced Layer does not have a significant impact on the network power consumption (maximum variation of 2.8%) as its level is at least 4 dB lower than the Core Layer and it is independent from the user's distribution in the area. The MCS in the Core Layer remains constant but there is a variation of 1.2 dB in the SNR for this layer caused by the LDM configuration. As a consequence the density of active LTE BSs does not have a significant variation. For the absolute maximum separation between the layers (7 dB) an 8.1% lower power consumption is achieved in the LTE eMBMS network. This is equivalent to a saving of 5.3 MW/year. The maximum separation between the layers in the LTE LDM configuration causes a lower radiated level in the Enhanced Layer. As the Core Layer configuration is the same, the standard deviation in the number of active BSs is lower than 7%. Most of the power consumption variations depend on the radiated power in the Enhanced Layer. Our optimization algorithm trends to switch to idle mode BSs with redundant Core Layer coverage. If a BS is switched to idle mode, the algorithm previously verify that other BSs can satisfy a similar equivalent coverage by the Enhanced Layer. This is because more active BSs rather than improving coverage might degrade it due to increased interference in a cell infrastructure with smaller cell coverage range.

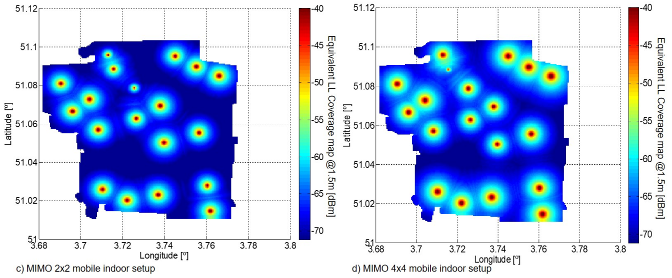
The achieved savings in terms of power consumption (by configuring a Enhanced Layer with lower power) might not be compensated by its harmful impact on the network performance. Fig. 6 shows the percentage of coverage by the Enhanced Layer compared to the normalized power consumption savings (in percentage) achieved by the LTE eMBMS network.

The maximum power consumption savings are achieved for the MCS 4/5 16-QAM and an injection level of -7 dB. However, because of a 3 dB lower signal level for the Enhanced Layer the coverage is reduced by 14%. A maximum



a) SISO fixed antenna outdoor setup

b) SISO mobile indoor setup



c) MIMO 2x2 mobile indoor setup

d) MIMO 4x4 mobile indoor setup

Fig. 7. Equivalent Enhanced Layer Coverage map for a) SISO fixed antenna outdoor setup, b) SISO mobile indoor setup, c) MIMO 2x2 mobile indoor setup, d) MIMO 4x4 mobile indoor setup.

saving of 5% can be achieved for the same MCS and an injection level of -6 dB without a significant degradation of the coverage, i.e., less than 1 % degradation compared to the coverage requirement (the dashed-dotted line is a reference for 95% of the area with service 99% of the time). The highest MCS (dotted line in Fig. 6) has the worst performance ratio in terms of power consumption savings to achieved coverage, with a near-linear slope (square fitting = 0.994) of -14.1% of coverage degradation per unit of power consumption saving.

C. Loss Compensation by MIMO Diversity

Fig. 7 shows the equivalent coverage map for the Enhanced Layer for a) SISO fixed antenna outdoor setup receiving a broadcasting service, and for different antennas configuration considering a mobile indoor setup: b) SISO , c) MIMO 2x2, d) MIMO 4x4.

For all the evaluated configurations the Core Layer coverage is in the range from 98% to 100%. However, in the Enhanced Layer, just the change from the outdoor configuration to indoor, causes a degradation of the coverage from 80.9% to barely 35%. This is caused by the additional losses in the receiving conditions for each setup, including lower antennas gain and building penetration losses. The MIMO setup with a 2 by 2 antenna array allows increasing the coverage probability to 78.4%, which is still below the quality guaranteed for the outdoor setup and the evaluated MCS. Notice that for this MIMO setup in a traditional LTE cell array it is possible to guarantee a coverage higher than 95%. However, the heuristic planning tool might not find an optimal for the Enhanced Layer service. This is because there is a trade-off between the Enhanced Layer coverage and inter-cell interference caused to the Core Layer service. For the MIMO 4x4 setup the coverage probability is increased to the 95% target achieving the best normalized Core Layer to Enhanced Layer coverage ratio of 1:0.95.

D. Effect of a higher MCS for the Core Layer

An instinctive assumption for achieving the intended coverage by the dual-layer LDM network is using similar MCSs for both layers or a higher MCS for the Core Layer in order to match both layers' coverage. However, only when the Core Layer is configured to have an SNR threshold lower than the injection level, the Enhanced signal interference does not significantly degrade the Core Layer detection performance [4]. For this reason, the MCSs and the injection level cannot be arbitrarily assumed, and they have a major impact on the network performance and coverage [39]. The minimum SNR requirement for decoding the Core Layer is related to the injection level (ratio of the power allocated to each layer which defines the layers separation). In this way a minimum injection level is required depending on the MCS for each layer. For instance, for using 1/2 16 QAM in the Core Layer the minimum injection level increases from -4 dB to 14.2 dB or 15.8 dB, depending on the MCS of the Enhanced Layer. This injection level is more than 10 dB higher than for 1/3 QPSK. In such case the number of BSs for satisfying the Core Layer coverage is increased to 41 (2 times higher) with a network power consumption of 2.2 times higher and an additional degradation of 0% to 10% on the Enhanced Layer coverage (for QPSK and 16 QAM respectively). For unicast applications demanding a higher bandwidth, the Enhanced Layer PRBs might be partitioned between the multicast and unicast service. However, this implies a higher power consumption for the mobile user terminals.

IV. CONCLUSION

In this paper we experimentally emulated the inter-cell interference of an LTE eMBMS network by means of a Wideband Communication Tester, capable of emulating the LTE BS infrastructure. Based on the experimental results an LTE eMBMS multilayered network is modeled.

Our experiments revealed that a higher Cell-Interference Margin has to be considered for the joint provision of unicast-broadcast services. For different network configurations we accounted for a maximum CIM of 4.8 dB (99^{th} percentile), which is 2.8 dB higher than for traditional LTE. This increased CIM has an impact on the Enhanced Layer coverage of a broadcasting service demanding more than 75 Mbps, for which the coverage is reduced by approximately 19%. Nevertheless, a target coverage of 95% of locations covered during 99% of the time can be guaranteed for delivering an ultra high definition media program demanding up to 51 Mbps. For multicast or unicast applications in the Enhanced Layer we explored the feasibility of MIMO diversity. In an indoor mobile configuration, a MIMO 4x4 antenna array is required for guaranteeing the intended target coverage in the evaluated scenario.

Future work will consist of assessing the computational performance and accuracy (mean square error) of Deep Neural Networks for optimizing multilayer 5G networks.

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