Enabling SFN Transmissions in 5G Cloud-RAN Deployments

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***Abstract*— In this paper, an innovative Radio Access Network (RAN) architecture design to enable Single Frequency Network (SFN) functionality in 5G Networks is proposed. SFN transmissions impose several challenges and delay constraints in distribution networks. To overcome this, a new functionality is developed by inserting a new logical entity, Centralized Coordination Entity (CCE), inside Cloud-RAN architecture. By leveraging 3GPP Release 15 gNB split functionality, and extending eMBMS SYNC protocol this proposal has minimal imprint over 5G Networks and can support a wide range of SFN transmissions. This design fulfils the requirements for Vehicular and Mission Critical communications, Linear TV distribution or IoT, while overcoming existing limitations in Release 14 eMBMS. A complexity analysis of this solution in terms of imprint over 5G Architecture, latency and dimensionality is used to validate the proposal.**

Keywords— 5G Networks, Multicast, NG-RAN, SFN, Cloud-RAN

I. Introduction

Single Frequency Networks is a type of wireless Point-to-Multipoint (PTM) communication where all involved transmitters are synchronously sending the same OFDM signal in the same time period [1]. The main advantage is an increase in coverage, since the Inter Cell Interference (ICI) is transformed into constructive gain, however, stringent delay conditions that affect the network and frequency planning are imposed. This technique is widely used in PTM standards, both in Digital Terrestrial Television (DTT) such as ATSC 3.0 [2], DVB-T2 [3], cellular based 4G eMBMS [4] or Radio Broadcasting like DAB [5].

In order to satisfy the delay requirements, a synchronization protocol to encapsulate the broadcast data, providing a constant stream of Time-to-Air (TTA) information to the transmitters is necessary. Note that, this is different from the common time reference used by the transmitters e.g. GPS or NTP. For example, in DVB-T2, T2-MI [6] protocol provides synchronization packets, in ATSC 3.0, STL [7] protocol coordinates the transmitters and in eMBMS, SYNC [8] protocol ensures that the cells are transmitting the same data.

The latest version of cellular technologies is Release 15, made by 3rd Generation Partnership Project (3GPP), and finished in December 2018. This Release was mainly focused on Point-to-Point (PTP) transmissions, so all considerations for PTM transmissions inside Release 15 were postponed to future Releases. Several Study Items (SI) involving multicast or broadcast transmissions are noteworthy [9] [10] [11]. Terrestrial broadcast [9] is currently assessing if Release 14 eMBMS is enough to fulfil 5G requirements, [10] is targeting support for multicast/broadcast for any verticals who can benefit from it and [11] will design an eMBMS based 5G solution only for receive-only-mode terminals leveraging the Service Based Architecture (SBA). These SIs are targeting Release 16 and Release 17.

Regarding Release 15 Radio Access Network (NG-RAN), the newest iteration on the NodeB is called gNodeB (gNB). One deployment option for the gNB splits the higher layer protocols: part of the traffic handling is performed in gNB Centralized Units (gNB-CU) and the rest is made in gNB Distributed units (gNB-DU). Additionally, and fully integrating Release 14 LTE Control and User Plane Separation (CUPS) [12] paradigm, the gNB-CU can be further split into gNB-CU Control Plane (gNB-CU-C) and gNB-CU User Plane (gNB-CU-U). This topology fully incentives a Cloud-RAN deployment, where the computation resources are dedicated dynamically to one powerful gNB-CU, and several less potent gNB-DU instances carry the data to the correspondent geographical location.

This paper is structured as follows: Section II covers the existing eMBMS limitations, while Section III presents the proposed architecture for coordinated transmissions in 5G RAN. For Section IV a complexity analysis in terms of features, dimensionality, imprint over 5G and latency is shown. The paper concludes with Section V, summarizing the ideas presented.

II. eMBMS Limitations

The current solution to provide broadcast services and capabilities to the 4G Core Network is eMBMS, an add-on on top of the existing LTE network with additional network entities. eMBMS first version was introduced back in 3G Release 8, known as MBMS. Over the years, the original system was gradually upgraded with new features and eventually migrated to 4G, while keeping a backwards compatibility philosophy with previous Releases [13]. This development paradigm introduced many limitations in the eMBMS solution, both at Radio and Core side. Many verticals which could benefit from Point-to-Multipoint transmissions, such as Public Warning, Internet of Things or Vehicular communications, could not use the system as it is. An overview of the most relevant limitations is shown in this section.

A. eMBMS limitations

Existing work in the literature such as [14] [15] and [16] have studied, addressed and proposed alternative architectures for eMBMS limitations. Related to this proposed solution, three limitations should be mentioned: Static broadcasting areas, lack of cell granularity and lack of address space in MBMS signaling. Going into detail, for the first limitation, any type of change to the Service Area where a MBMS session is being broadcasted implies a service interruption and relaunch, which is not acceptable for some reliance dependent applications like V2X or Mission Critical. Continuing with the second limitation, some events are characterized with unpredictable time or geographical location such as natural disasters, in order to broadcast alarm messages in those areas without outreaching the affected zone, cell granularity for broadcast is needed. For the final limitation, the address space is governed by the Service Area Identifier (SAI), which has a range of 0 to 65535, limiting the number of reachable cells. In a nation-wide broadcast deployment, considering both High Power High Tower (HPHT) and gap-fillers, this limit can be easily reached and hinders the deployment.

B. Motivation on overcoming limitations

3GPP Rel-14 eMBMS provides suitable mechanisms for the static configuration of different broadcast coverage areas. As previously mentioned, the specified SFN framework is static in terms of service allocation and the mechanisms are mostly oriented for SFN deployments. However, there is a motivation to overcome the architectural limitations and challenges to allow operators to break the paradigm of add-on SFN deployments to existing networks with static service offering. 5G should bring in the capability to integrate the content delivery using SFN networks to the common 5G framework. The 5G should allow synchronized dynamic geographical SFN to deliver the service instead of operating a statically configured SFN areas. The state-of-the-art SFN networks should offer a variety of deployment options. The use of a common 5G architecture, based on the existing unicast architecture, will minimize the implementation complexity of the RAN and allow dynamic SFN deployment options and service offering.

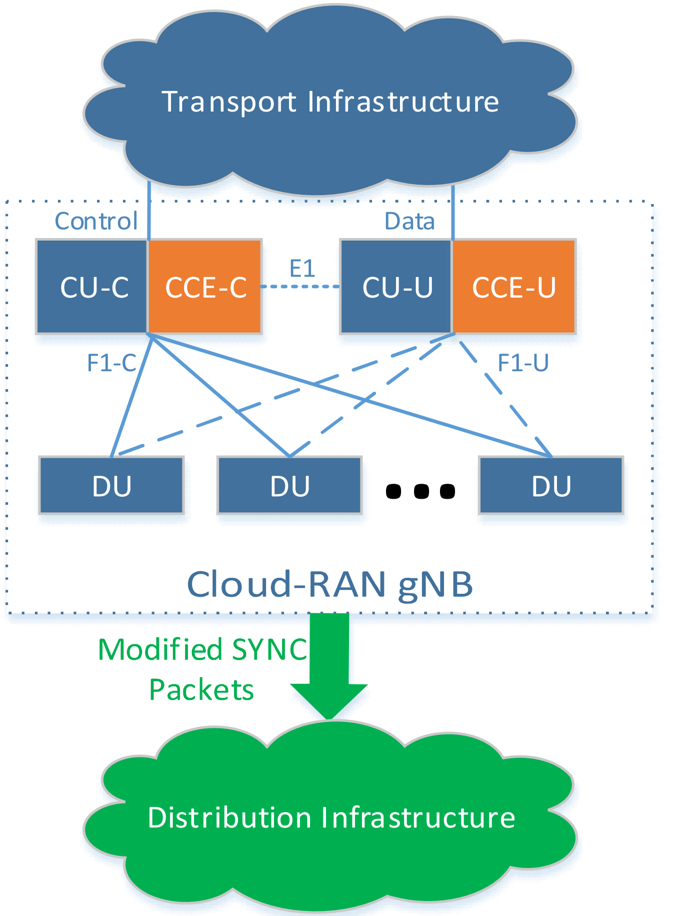

Figure 1: Cloud-RAN gNB with the new Centralized Coordination Entity, providing SFN capabilities to 5G transmissions.

III. Proposed Architecture

The proposed architecture is a Cloud-RAN formed by just one gNB. This gNB is split between one gNB-CU and several gNB-DU. At the same time, each gNB-DU is connected to several Remote Radio Heads (RRH) via the distribution infrastructure, which contains the transmitter cells at the end. This topology forms a tree-like structure, in line with existing 3GPP specifications. A new logical entity, called Centralized Coordination Entity (CCE) is introduced inside gNB-CU. This CCE can be also split into CCE Control Plane (CCE-C) or CCE User Plane (CCE-U). Figure 1 illustrates the overall architecture. Target devices are both terminal with uplink capabilities and receive-only terminals.

To fulfil the SFN requirements, the CCE incorporates two main functionalities, one involving the Control Plane and the other related to the User Plane: The Control Plane part is the setup of the SFN area inside cellular networks, deciding the physical layer parameters such as modulation, code rate and scheduling to satisfy specific Quality of Service (QoS). This decision is propagated using new signaling towards the relevant gNB-DU, which will relay this to the relevant RRH.

Also, the CCE-C can take into account existing unicast measurement reports to fine tune the physical layer parameters of the SFN transmission.

The second functionality is the constant encapsulation of the multicast data to provide TTA information for the cells involved in the SFN transmission. A modified eMBMS SYNC [8] is used as the encapsulation protocol, but instead of manually setting the SYNC parameters between the eMBMS Core and the eNBs, the parameters are negotiated in the SFN setup process of the CCE-C. This approach simplifies the operating process and improves the deployment speed. Note that, in this case, the entity encapsulating the data resides inside the RAN, while in 4G eMBMS, SYNC is applied at the BM-SC.

This architecture fully leverages one of the main novelties of 5G: the replacement of QoS flows instead of Radio Bearers. By exploiting this, pre-assigned QoS flows for SFN can be defined in the 5G Core connected to the CCE, in order to trigger the SFN transmissions, allowing the multiplexing of unicast and broadcast data on the same radio sub-frames. The connection to a 4G eMBMS Core Network is also supported by implementing the M3 interface for the Control Plane [17].

Broadcast/multicast SFN transmission enabled gNB uses the Service Data Adaptation Protocol (SDAP) layer where the modified CCE-U will receive the broadcast/multicast traffic and identify the type of traffic based on the QoS flow identifier and/or through the context associated with the flow. For broadcast/multicast traffic, the CCE-C can dynamically configure (add, modify, remove) the gNB-DUs within the SFN service area based on the definition of SFN service area coverage. In 5G, the terminals are expected to provide neighbor cell measurement reports and feedback of the traffic the UE is receiving. For broadcast traffic, the SDAP can map the flows into broadcasted data radio bearer or specific multicast radio bearer with support for signaling information for broadcast. Flows are broadcasted using the broadcast channels by the appropriate multi-cell SFN setup of CCE-C determined based on the SFN service area where the data needs to be multicasted or broadcasted.

In Cloud-RAN deployment, the split into gNB-CU and gNB-DU allows RAN functions with higher layer processing of SDAP and Packet Data Convergence Protocol (PDCP) at CCE. The DU(s) closer to the deployed cells receive information about the SFN transmission parameters from CCE-C and the CCE-U provides the broadcast/multicast traffic to DU for SFN transmission. The Layer 2 radio protocol architecture for Cloud-RAN assumes that the RLC entities are located in DUs and DU controls the transport channels for the transmission. Therefore, the RLC layer may not be placed in the same Cloud-RAN computing hardware pool as the CCEs.

The CCE-C configures CCE-U via E1 interface to trigger modified F1 interface setup for gNB-DUs which belong to the broadcast/multicast transmission list. Here the modified F1 represents a logical interface between gNB-CU entity and gNB-DU entity, where the interface can be a unicast or a multicast tunnel of broadcast/multicast radio bearer, e.g. GTP-U over IP multicast as used in M1 interface of eMBMS. The CCE-U acknowledges tunnel establishment for the requested SFN radio bearers. It is also possible to setup the tunnel as unicast tunnel and further modify to broadcast/multicast tunnel. In multicast/broadcast SFN network the session context holds information about multicast/broadcast QoS flow(s) and multicast/broadcast bearer(s) and the context is associated with a multicast group.

The CCE-C configures the associated gNB-DU with the SFN transmission parameters, including the transmit power, reference signal configurations and possible subframes for broadcast/multicast transmissions. This enables the gNB-DUs to transmit the same data using the same physical radio resources thereby appearing as a single SFN transmission to the UE according to Figure 2. When the configuration takes place as part of the gNB-CU CCE-C and CCE-U in NG-RAN, the static pre-configuration of broadcast/multicast from 5GC can be avoided.

RRH or transmitters involved in the SFN transmission can be attached (or modified) to dynamically created DUs. These dedicated DUs can multicast their broadcast packets to every transmitter pending from it, thus solving the static allocation limitation of geographical areas in eMBMS. In the case that one DU is overloaded by unicast and broadcast traffic, a new DU instance can be launched inside the gNB to share the load.

Depending on the transmitters involved in the SFN, two different scenarios arise: either all transmitters are served by the same DU or the transmitters in the SFN belong to several DUs (see Figure 2). The main implication derived from this is the divergence in packet processing time and distribution delay of the all possible data paths, which must be compensated in the TTA SYNC timestamps inserted by the CCE-U. On the one hand, for only one DU SFN scenario, only the difference in packet arrival time from several transmitters is relevant. On the other hand, for several DUs SFN, depending on the particular computational load and QoS parameters, a process time correction of broadcast packets must be added on top of the packet arrival time difference.

The DUs allocated to SFN transmission contain a list of cells forming the SFN service area. The CCE-U delivers the SFN data to the corresponding DUs. When the data is being transmitted over the Physical Downlink Shared Channel (PDSCH) based on scheduling and transmission parameters, the corresponding Downlink Control Information (DCI) through the Physical Downlink Control Channel (PDCCH) indicates the Radio Network Temporary Identifier (RNTI) which the UEs can decode. In case of broadcast/multicast the Group RNTI is allocated to a group of UEs who may be receive only devices, or in case of dynamic SFN areas a group of UEs who have indicated their interest in receiving

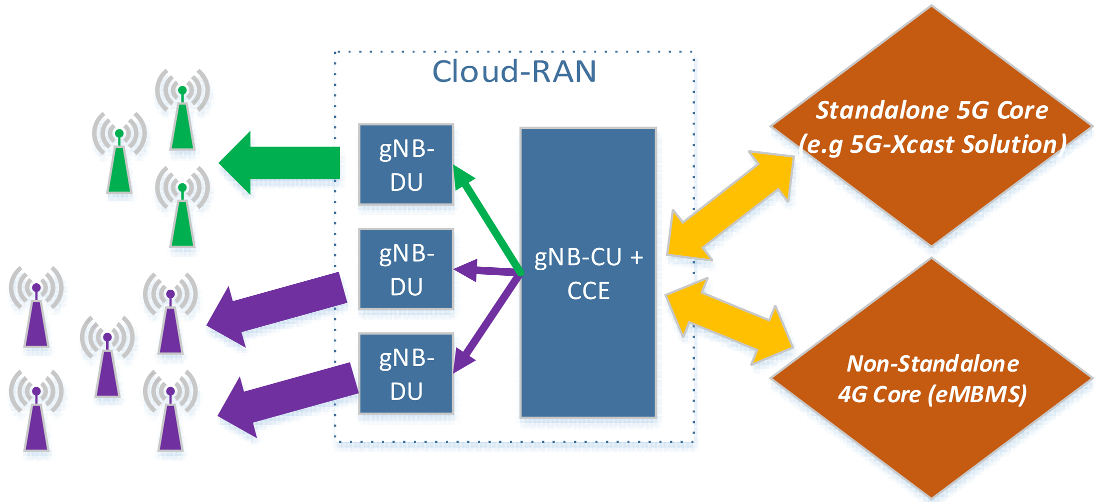

Figure 2: End to End system with the proposed Cloud-RAN solution. This RAN is agnostic to the overlying Core Network. Two different SFN scenarios are shown, depending on how many DUs are involved in the coordinated transmission. Divergence in delay experienced by the broadcast packets among all possible data paths must be compensated by the newly introduced CCE in the gNB-CU.

broadcast/multicast traffic. The broadcast/multicast over SFN with G-RNTI allows any UE to receive the broadcast/multicast data over the PDSCH.

IV. Complexity Analysis

The system proposed is formed by one gNB for the entire deployment. Nation-wide SFNs for broadcast are characterized for having a large number of cells, both deployed in High Power High Tower (HPHT) and some used as gap-fillers. In this section, it is analyzed if the system presented in this paper could be used to control and distribute nation-wide SFN, and what are the implications in terms of latency, capabilities and added imprint over the specified 5G architecture.

A. *Imprint analysis*

Modified eMBMS SYNC controlled by RAN is proposed to reside between CCE-U and DU allowing controllable fronthaul latencies. The number of new interfaces impacts directly the service integration and deployment complexity of the new broadcast/multicast system. Possibility to reuse and enhance current NG-RAN interfaces to support broadcast and multicast will keep the complexity low. 3GPP has defined interfaces between the NG-RAN and 5GC and specified reference point N2 for Control Plane and reference point N3 for User Plane. The NG-RAN internal interfaces are those between 5G RAN logical network nodes. Enabling the CCE-C to control the 5G broadcast/multicast and modified CCE-U as part of the gNB-DU internal interfaces minimizes the need for new interfaces.

B. *Radio Resource Efficiency*

Broadcast/multicast through the 5G PDSCH with basic limited uplink feedback channel allows dynamic deployment of SFN network. SFN transmission involving multiple cells for group transmission improves the spectral efficiency especially at the cell edges when the control of the SFN resides at the CCE-C.

C. *Scalability*

Broadcast/multicast with SFN transmission requires one resource allocation for the UE group. In case the SFN service areas are semi-static and no uplink channel feedback is expected from the UEs, the amount of radio resources would be independent of the number of UEs. When the SFN areas are operated in dynamic manner taking the UE interest in receiving the broadcast/multicast, then resource allocation done per UE group and the dynamic radio resource utilization in SFN is not proportional to the number of users even if unlimited number of users may not be supported. SFN transmission in NG-RAN is natively supported feature and the SFN broadcast/multicast architecture is integrated into the baseline unicast architecture maximizing the scalability and enabling dynamic switching between different transmission modes for transparent 5G broadcast networks.

D. *Dimensionality analysis*

As previously mentioned, the architecture follows a tree-like topology, where one gNB-CU with a CCE serves a large amount of gNB-DU over F1 interface, and the gNB-DUs serve a large amount of RRH/cells. In [16], it is specified that the maximum number of gNB-DU under one gNB-CU allowed by the signaling is 2^{36}-1, and the maximum number of cells under one gNB-DU is 512 or 2^9. Overall, the maximum number of cells served is $(2^{36} – 1) * 2^{9}$. To the best of authors knowledge, this value greatly exceeds any existing DTT deployment.

On other vein, the biggest limitation factor for nation-wide SFN deployment in 5G is the Inter-Site Distance (ISD) allowed by New Radio numerologies. As shown in [19], maximum ISD in Release 15 is 1.41 Km. Fortunately, new physical layer schemes such as the negative numerologies proposed in [19] could extend this up to 120 Km, perfectly fit for nation-wide SFN.

E. Latency analysis

Latency performance parameters in cellular networks are usually divided in Control Plane latency and User Plane latency. In detail, Control Plane latency is the time needed from an idle terminal to switch into a connected state, with context information in the Core Network, while the User Plane latency is the time spent by a packet from the source until it is decoded by the device. Given that the one of the design decisions of this architecture was to minimize the imprint over existing 5G solution, the results obtained by 3GPP can be applied to this approach. For standard devices, this Control Plane and User Plane latency is the same as Release 15 latency i.e. around 15 ms [20] and 2 ms [19] for Control and User Plane respectively. Possible upgrades to these values is the use of the newly introduced 5G RRC_INACTIVE state which can lower the overall "wake-up" latency from power efficient state to connected mode, and the use of Multi-access Edge Computing (MEC) to bring the source content closer to the user.

V. CONCLUSION

In this paper, a new 5G Cloud-RAN architecture which supports SFN transmissions is presented. The architecture has one central gNB-CU and a dynamic number of gNB-DUs. By introducing a new logical entity, the CCE, SFN operation is possible. CCE can be divided into Control procedures, i.e. SFN Setup; and on the other hand User procedures, i.e. Data Encapsulation. The complexity analysis shows that the proposed broadcast/multicast SFN transmission scheme can provide benefits in terms of radio resource utilization, scalability and deployment. Also, a dimensionality analysis proving that this deployment can manage existing nation-wide SFN is shown.

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