5G Mixed Mode: An Innovative Point-to-Multipoint Solution for New Radio

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Abstract—**This work presents a potential solution for enabling the use of multicast in the 3GPP Release 15 air interface, called 5G New Radio (NR). The proposed multicast mode, denoted as 5G Mixed Mode follows one of the two approaches envisaged in 3GPP, which enables a dynamic and seamless switching between unicast and multicast, both in the downlink and the uplink. This paper also provides a performance evaluation in Single Frequency Networks (SFN) and mobility scenarios, showcasing the potential advantages of this solution over unicast in relevant scenarios.**

Index Terms—**5G; New Radio (NR); SC-PTM; Single Frequency Networks (SFN); Point-to-Multipoint (PTM)**

I. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) normative work for the 5G IMT-2020 submission started in March 2016 with the Release 15 (Rel-15), which was structured in three phases. An early-drop 5G non-standalone (NSA) version was approved in December 2017. It relies on both 4G Long Term Evolution (LTE) and 5G New Radio (NR) air interfaces and reuses the LTE core network for the control plane. In June 2018, a 5G standalone (SA) version was specified. It additionally includes a fully-capable 5G Core network (both user and control plane capabilities) improving efficiency with lower costs. The last drop of Rel-15 is expected to be released in March 2019, enabling the 5G Core inter-work with both LTE and NR Radio Access Network. The new 5G system will be continued during Rel-16 to meet the requirements defined in [1] and [2].

The NR Rel-15 air interface brings a large number of improvements compared to LTE to address the IMT-2020 requirements [3] as well as to cover an extensive number of use cases for the digitization of new verticals. Some of the most important improvements in the air interface are more efficient Forward Error Correction (FEC) coding schemes [4], [5], larger bandwidths, new OFDM waveform numerologies adapted to the 5G spectrum band allocation or massive Multiple-Input Multiple-Output (MIMO) schemes. However, NR Rel-15 has only focused on unicast point-to-point (PTP) transmissions, which may not be sufficient for scenarios where a very large number of users consume the same data, such as popular media content, emergency messages or software updates [6]. In those scenarios the use of multicast/broadcast point-to-multipoint (PTM) schemes can offer huge capacity gains, ensuring a cost-effective high-quality delivery mechanism [7]. The lack of PTM capabilities may imply a future limitation of 5G networks, leading to inefficient service provisioning and utilization of the network and spectrum resources. Moreover, 3GPP identified a flexible multicast service as a basic feature to be used in 5G [1], [2]. A Work Item on LTE-based 5G Terrestrial Broadcast [8] and a Study Item on NR mixed mode broadcast/multicast [9] were drafted in June 2018. While the former was accepted with the objective of capturing a gap analysis of LTE Rel-14 to meet the broadcast requirements [10], [11], the latter, which aims at studying different aspects to enable broadcast/multicast over NR was noted for Rel-17. This paper introduces a PTM design that enables a dynamic allocation of unicast and multicast resources over NR following the principle designs of [9]. This extension, named 5G Mixed Mode, is split into two variants. On the one hand, 5G Single-Cell Mixed Mode (SC-MM) reuses as much as possible the existing NR air interface components. However, it requires some modifications to enable the efficient transmission over several users camped in the same cell demanding the same data content. On the other hand, 5G Multiple-Cell Mixed Mode (MC-MM) takes the SC-MM design as a basis and adds new modifications to dynamically deliver PTP and PTM content over multiple synchronized cells.

The rest of the paper is structured as follows: Section II briefly describes the main new features of the NR Rel-15 air interface, paying special attention to the enhanced waveform flexibility [6]. Section III highlights the NR air interface modifications needed for the proposed SC-MM and MC-MM solutions. They are next evaluated and compared with current NR PTP system analytically and by means of link level simulations in Section IV. Finally, the conclusions are summarized in Section V.

II. 5G NEW RADIO FOR UNICAST SERVICES

This section provides a brief description about the first 3GPP specification of NR, i.e. Rel-15, which presents a more flexible design than LTE to fulfill a wider set of heterogeneous requirements.

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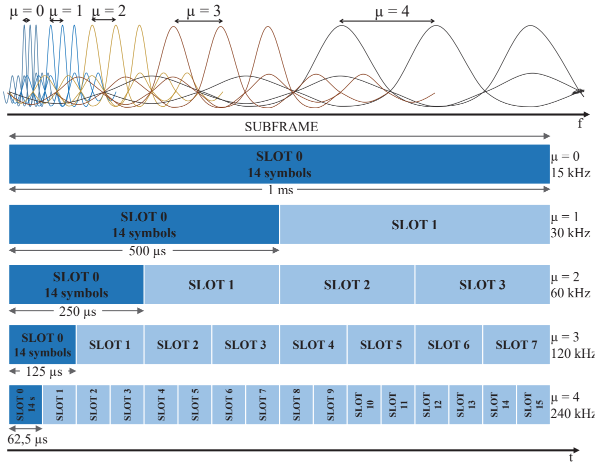

Fig. 1. NR numerologies (μ) (top), and associated slots duration time (bottom).

A. *Waveform and Numerology*

As LTE, NR has adopted CP-OFDM waveform for both downlink and uplink. However, the biggest difference between both specifications is the use of new numerologies (subcarrier spacing and symbol length) in NR. Whereas LTE has a fixed subcarrier spacing of $\Delta f = 15$ kHz, NR support multiple types according to the parameter μ as $\Delta f = 2^{\mu} \times 15 = \{15, 30, 60, 120, 240\}$ kHz. In time domain, the higher the numerology (μ), the shorter the OFDM symbol length, and consequently the shorter the slot duration. NR reduces the delivery of low latency applications, thanks to the shorter slot durations, as well as to the introduction of mini-slots, but they are also useful in massive MIMO beamforming procedures. Fig. 1 depicts the different numerologies included in NR specification. It should also be remarked that the new NR slot structure allows for a dynamic assignment of the link direction in each OFDM symbol within the slot, minimizing the potential uplink and downlink traffic congestions.

B. *Physical Channels and Signals*

Channels are known as flows of information transmitted between the different protocol layers. Thanks to them, different types of data are separated and transported across different layers. In particular, physical channels carry MAC layer information, and are differentiated between downlink and uplink transmissions.

1) Physical Downlink Channels and Signals: Three physical downlink channels and five physical downlink signals are defined. They differ on their functionality.

- **Physical Broadcast Channel (PBCH)**: transmits the static part of the System Information, known as Master Information Block (MIB), to any User Equipment (UE) requiring to attach the network.
- **Physical Downlink Control Channel (PDCCH)**: Specifies the scheduling and allocation of the data content for every UE by means of the Downlink Control Information (DCI). This information is mapped within the PDCCH in CORESETs, whose size depends on the Aggregation Level (AL). It also configures Hybrid Automatic Repeat Request (HARQ) retransmissions, link adaptation and MIMO parameters.
- **Physical Downlink Shared Channel (PDSCH)**: Transmits the data content to the UE and the System Information Blocks (SIBs).
- **Primary and Secondary Synchronization Signals (PSS, SSS)**: Combined with the PBCH they allow the UE to access the NR network. Specifically, they provide radio frame timing information and cell ID at the initial search, as well as beam management in IDLE state.
- **Demodulation Reference Signals (DMRS)**: They are used for channel estimation in order to retrieve the information in PBCH, PDCCH and PDSCH.
- **Phase Tracking Reference Signals (PTRS)**: They are only used at Frequency Range 2 (FR2) 24.25 GHz - 52.6 GHz for phase noise estimation in the PDSCH.
- **Channel State Information Reference Signals (CSI-RS)**: Used to provide CSI, needed for link adaptation and for beam management in CONNECTED state.

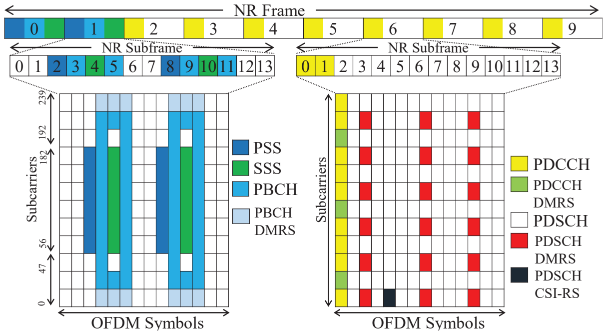

Fig. 2. Framing structure for a NR frame with all slots configured as downlink.

Fig. 2 shows where physical downlink channels and signals are allocated, when all the slots of a frame are configured as downlink (Slot Format Indicator = 0).

2) Physical Uplink Channels and Signals: Three physical uplink channels and three physical uplink signals are defined in NR. Their names and functionalities are listed below.

- **Physical Random Access Channel (PRACH)**: Used by the UE to request the uplink initial access, as well as for beam management processing.
- **Physical Uplink Control Channel (PUCCH)**: It carries the Uplink Control Information (UCI) that contains different information such as CSI, HARQ retransmission and scheduling requests.
- **Physical Uplink Shared Channel (PUSCH)**: Transmits the data content to the Next Generation Node B (gNB), and it can optionally convey UCI transmissions.
- **Demodulation Reference Signals (DMRS)**: Used for channel estimation in order to allow the proper demodulation of PUCCH and PUSCH.

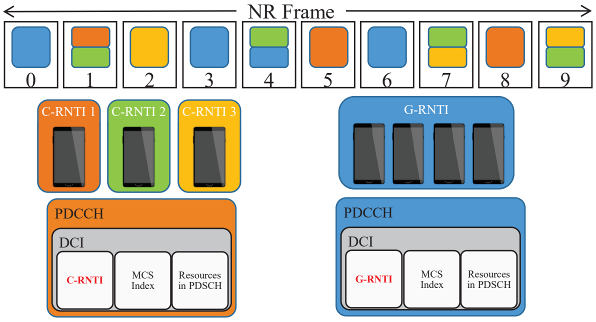

Fig. 3. C-RNTI for NR PTP versus G-RNTI for SC-MM PTM.

- **Phase Tracking Reference Signals (PT-RS)**: Used for the same functionalities than in downlink.
- **Sounding Reference Signals (SRS)**: Equivalent to CSI-RS for uplink, providing CSI to the gNB for link adaptation and scheduling configurations.

III. 5G MIXED MODE DESIGN

Although the Rel-16 air-interface will improve some of the limitations found in previous releases, it will not include as an enhanced feature. This limitation can be solved with the proposed design. One of the key principles adopted for the proposed design is to limit investment costs and implementation complexity over the existing PTP infrastructure by minimizing the added footprint for delivering PTM services.

A. Single-Cell Mixed Mode (SC-MM)

SC-MM has been designed considering the current NR Rel-15 as a reference. It reuses as much as possible the existing air interface components, i.e. channel coding, framing, and physical channels. Only some changes in the physical control channels are introduced.

1) Modifications introduced in PDCCH: As explained previously, the PDCCH plays a key role in the reception of scheduling information and de-scrambling of data by means of the Cell-Radio Network Temporary Identifier (C-RNTI). Proceeding in the same manner as the Single-Cell Point-to-Multipoint solution of LTE [12], it is possible to define a common identifier, Group-RNTI (G-RNTI), so that several UEs interested in the same content transmitted over a single cell can be easily grouped. The introduction of the G-RNTI enables a dynamic, flexible and scalable scheduling between unicast and multicast data within the PDSCH channel. The basic mechanism behind this process is illustrated in Fig. 3. As it can be observed, thanks to the introduction of G-RNTI, a single DCI could be transmitted for a group of UEs interested in the same content. This solution avoids the transmission of several CORESETs announcing the same data to all users and reduces considerably the PDCCH overhead within a NR frame.

2) Modifications introduced in PUCCH: Feedback procedures are possible thanks to the use of the uplink. They are also known as link adaptation schemes, such HARQ or Adaptive Modulation and Coding (AMC). The use of AMC schemes (Outer/Inner Loop Link Adaptation - OLLA/ILLA) can be considered as one of the most efficient feedback solutions in multicast contexts [13].

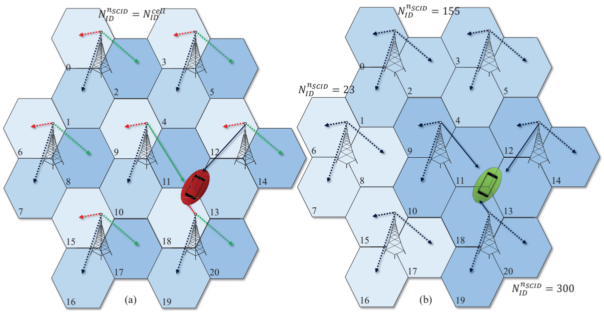

Fig. 4. Cell scrambling sequence initialization $N_{ID}^{n_{SCID}}$ according to the physical layer cell ID (a), and given by the higher-layer parameter *DL-DMRS-Scrambling-ID* (b).

With the aim of reducing the uplink signaling overhead, and based on [14] proposed for Single-Cell Point-to-Multipoint (SC-PTM), a dynamic link adaptation scheme with only CQI feedback is proposed. This mechanism called enhanced-OLLA (eOLLA) biases the received CQI values by an offset (Λ) dependent on the number of UEs (k) as $CQI_{biased} = CQI - \Lambda(k)$. From the simulations results provided in [14], it was shown that this basic and biased solution provides a similar performance as transmissions with both CQI and HARQ feedback, but simplifying receiver's design and implementation complexities.

B. Multiple-Cell Mixed Mode (MC-MM)

One of the main drawbacks of SC-MM is the inefficiency to cover large areas due to inter-cell interferences. The coverage can be extended by means of cell coordination mechanisms, like Single Frequency Network (SFN) deployments. The following air interface modifications are proposed to enable SFNs, resulting in the defined MC-MM design.

1) Common Cell Scrambling Sequence: In SFN deployments, the same content should be transmitted from different sites. This requires not only to transmit the same data content but also in the same resources elements, as well as the same control content, including DMRS values. All this information is determined with the cell specific scrambling sequence, which its initialization depends on $N_{ID}^{n_{SCID}}$ parameter. Instead of performing the widespread physical layer cell ID procedure that would lead to a different scrambling sequence per cell, MC-MM forces it to a certain value, $N_{ID}^{n_{SCID}} \in \{0, 1, , 65535\}$ for all the coordinated cells, which will be given by the higher-layer parameter *DL-DMRS-Scrambling-ID*. Figure 4 illustrates the $N_{ID}^{n_{SCID}}$ traditionally used (left) and with the proposed parameter for MC-MM (right).

2) Negative Numerologies and Extended CP: The maximum Inter-Site Distance (ISD) between SFN transmitters is limited by the CP length, which in turn depends on the NR numerology. The maximum ISD with current Rel-15 is 1.4 km. This ISD may be suitable for some limited scenarios such as

TABLE I
ISD FOR EXTENDED CP WITH NEGATIVE μ

μ	Δf (kHz)	T_U (μs)	T_{CP} (μs)	ISD (km)	Overhead (%)
0	15	66.6	16.6	5	20
-1	7.5	133.3	33.3	10	
-2	3.75	266.6	66.6	20	

stadium, campus or malls, but urban or rural environments are characterized by longer distances. To support these scenarios, a set of different enhancements may be introduced. Longer CP lengths can be obtained by employing narrower Δf and by making use of the extended CP type adopted in NR[1]. In particular, two negative numerologies in conjunction with Extended CP are proposed for MC-MM as shown in Table I. However, these solutions will lead to greater vulnerability in high-speed conditions and will require larger a more complexity demanding FFT sizes. In addition, since the associated slots of negative numerologies will be spanned over more than one subframe, the use of mini-slots (e.g. slots of 2, 4, or 7 OFDM symbols) will be needed for compatibility reasons with NR framing structure [15].

IV. PERFORMANCE EVALUATION

This section evaluates the performance of the 5G SC-MM and MC-MM air interface solutions. The signaling overhead, SFN coverage, and mobility tolerance are analysed.

A. *Signaling overhead*

The enhanced flexibility of 5G NR reduces the required signaling overhead compared to LTE. On the one hand, Signaling and synchronization mechanisms for the correct reception and discovery of services are conveyed in PSS, SSS, PBCH, which jointly form SS/Block (SSB). A set of $L = \{4, 8\}$ SSBs, defined as SSBurst, is transmitted according to μ and the frequency band [16] for beam sweeping acquisition procedures in a half frame. Hence, this overhead is not dependant on the numer of serving users, so that the proposed solutions cannot reduce the amount of resources associated with it. On the other hand, a dedicated DCI is sent to each serving user by means of CORESETs that are conveyed in PDCCH. One CORESET occupies from 1 to 16 Control Channel Elements, which are constituted by 6 Resource Element Groups, which in turn are formed by 12 REs. Hence, a CORESET can be expanded from 1x6x12 = 72 REs to 16x6x12 = 1152 REs per frame and UE. As it is explained in Section III-A1, thanks to the use of a G-RNTI, a single CORESET can be transmitted to a group of users demanding the same content, reducing the resources needed for PDCCH. Hence, spectral efficiency gains compared to NR PTP can be expected for a large number of serving users demanding the same content. Table II shows the SSB and PDCCH overheads for NR with current Rel-15 and with the proposed 5G-MM for numerology $\mu = 0$ with 20 MHz[2] and 50 MHz[3] [17]. As it can be noticed, SSB overhead remains invariant regardless of the number of users, but PDCCH overhead increases up to 14% with 20 served users within the same cell. If a single multicast CORESET is transmitted in 5G-MM, the PDCCH overhead remains independent of the number of serving users with a 0.69% of overhead, leading to significant higher spectral efficiencies.

TABLE II
5G NR AND 5G-MM SIGNALING OVERHEAD FOR 20 AND 50 MHZ BANDWIDTH

5G system	Channel	REs	20 MHz OH	50 MHz OH
Both	SSB f <3 GHz	3840	1.14 %	0.42 %
	SSB f >3 GHz	7680	2.29 %	0.85 %
5G-NR	PDCCH 1user	1152	0.69 %	0.25 %
	PDCCH 10 users	11520	6.86 %	2.54 %
	PDCCH 20 users	23040	13.72 %	5.08 %
5G-MM	PDCCH 1 user	1152	0.69 %	0.69 %
	PDCCH 10 users	1152		
	PDCCH 20 users	1152		

B. *SFN Coverage*

SFN coverage is expressed as the variation of the required CNR depending on the relative echo delay. To carry out its evaluation, the 0 dB echo channel model [18] has been extended to allow the configuration of multiple echo delays inside and outside the CP region. Coverage has been analysed by means of link-level simulations for the NR Rel-15 ($\mu = 0$), and MC-MM modes with the proposed negative numerologies ($\mu = -1, -2$) for a Block Error Rate BLER $\leq 0.1\%$ and Modulation and Coding Scheme (MCS) 2. A real channel estimator formed by a linear interpolation in time domain followed by a FFT interpolation in frequency domain is used. Figure 5 depicts the required Carrier-to-Noise Ratio (CNR) versus echo delay for the three numerologies under study. As it can be seen, the performance remains constant for all the evaluated configurations for echo delays shorter than CP length. However, when echoes arrive between the CP and the Nyquist limit (T_p) [18], a degradation is observed until the echo arrives outside the Nyquist limit, so that the system is not able to achieve Quasi-Error Free (QEF) conditions. From the three configurations, it can be seen that $\mu = -2$ will even allow an acceptable performance for echo delays of 100 μs, which approximately represents ISD = 30 km.

C. *User Speed Tolerance*

Mobility has been evaluated by using a Typical Urban (TU-6) channel model with different user speeds. Real channel estimation (linear in time, FFT in frequency) with MCS 2 is used in all cases. Results in Figure 6 show that the use

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[1] While Normal CP length is obtained as $T_{CP} \simeq \Delta f/16$, Extended CP length represents $T_{CP} \simeq \Delta f/4$.

[2] 20 MHz, $\mu = 0$: 100 RB x 12 RE/RB x 14 OFDM symb/subframe x 10 subframes/frame = 168000 REs in one frame

[3] 50 MHz, $\mu = 0$: 270 RB x 12 RE/RB x 14 OFDM symb/subframe x 10 subframes/frame = 453600 REs in one frame

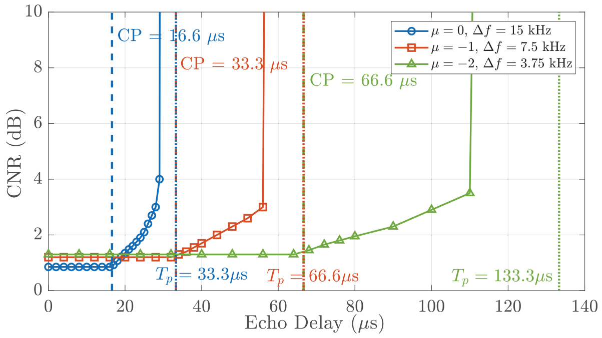

Fig. 5. Required CNR against echo delay for the proposed $\mu = \{0, -1, -2\}$ of 5G MC-MM with the 0 dB echo channel.

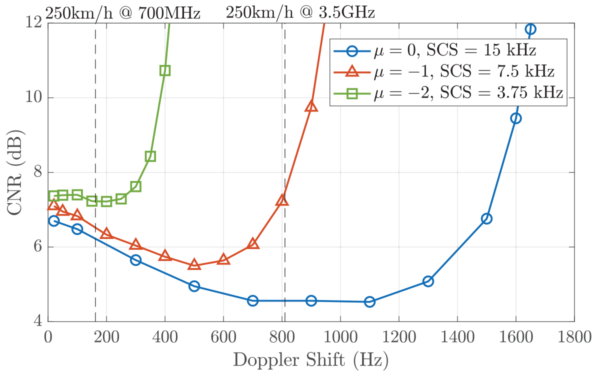

Fig. 6. CNR against user speed for the proposed 5G SC/MC-MM with TU-6 channel.

of a different numerology has a great impact on the mobility tolerance. The mixed mode allows Doppler shifts of up to 1600 Hz with numerology $\mu = 0$, equivalent to 2470 km/h and 500 km/h in the UHF band (700 MHz) or at 3.5 GHz, respectively. The other two numerologies, i.e. $\mu = -1$ and $\mu = -2$ reduce the maximum speed to 900 and 400 Hz, equivalent to 1380 and 620 km/h at 700 MHz band, and 270 and 120 km/h at 3.5 GHz band, respectively. Therefore, the MM negative numerologies can address the IMT-2020 speed requirement of user speed tolerance $v \geq 250$ km/h in the UHF band, but only $\mu = -1$ fulfils this KPI requirement at 3.5 GHz.

V. CONCLUSIONS AND FUTURE WORK

This paper extends the air interface of 3GPP 5G New Radio (NR) Release 15 (Rel-15) to point-to-multipoint (PTM) communications. The proposed mechanisms, called Single-Cell Mixed Mode and Multiple-Cell Mixed Mode, enable a flexible, dynamic and seamless switching between unicast and multicast transmissions in both downlink and uplink. They have been envisaged for different 5G verticals including media, public warning and Internet of Things (IoT). The key principle design is to ensure the maximum compatibility with the current NR Rel-15 by reusing the original air interface as much as possible. The required modifications include the introduction of a Group Radio Network Identifier, a multiple cell coordination for supporting Single Frequency Networks (SFN), or narrower subcarrier spacings in order to allow larger inter-site distances. The proposed modes increase the user spectral efficiency by reducing control overhead. In addition, the support of larger SFN distances with the negative numerologies of Multiple-Cell Mixed Mode has been validated through link level simulations as well as their tolerance against user speeds above 250 km/h.

As future work, the validation of the Mixed Modes needs to be longer developed against other relevant KPIs, such as spectral efficiency, latency or connection density. In addition, potential modifications in upper layers, should be investigated to confirm the compatibility with with following NR releases.

ACKNOWLEDGMENT

This work was supported in part by the European Commission under the 5GPPP project 5G-Xcast (H2020-ICT-2016-2 call, grant number 761498). The views expressed in this contribution are those of the authors and do not necessarily represent the project.

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