Agenda Item: 8.1.8
Source: National Taiwan University
Title: **NR and LTE Coexistence Assisted by Embedded-GFDM**
Document for: Discussion and Decision

1 Introduction

5G new radio (NR) technology highlights three high level use cases: enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable and low latency communications (URLLC) [1]-[2]. To make these visions come true, it is essential to consider the spectrum engineering comprising waveform design [3], multiple access scheme [4], and fragmented spectrum usage [5]. In particular, facilitating 5G users adopting different radio access technologies (RATs) to coexist with incumbent 4G users in current licensed long term evolution (LTE) bands is in urgent need, since many upcoming 5G applications require backhaul signaling/processing provided by widely-deployed LTE infrastructure and physical characterizations of the bands below 6 GHz for wide coverage and mobility support [6]-[7]. However, in practice, the mutual interference arising from their different subcarrier spacings, spectral sidelobes, and asynchronous operations makes the realization of such heterogeneous spectrum access quite difficult. Therefore, a major task now is to enable the licensed LTE band sharing with different RAT in an efficient way.

In this document, we investigate an LTE downlink band sharing with a 5G RAT (5GRAT) whose subcarrier spacing is narrower than the normal subcarrier spacing (15kHz) defined in 4G orthogonal frequency division multiple access (OFDMA) technology. A well-known example to this case is narrowband internet of things (NB-IoT) with in-band operation (i.e., utilizing the resource blocks in existing LTE transmission bands), which may choose 3.75kHz as its downlink subcarrier spacing [8]. As illustrated in Figure 1, the spectral sidelobe leakage caused by the legacy OFDMA transmission can significantly interfere with 5GRAT. How to efficiently cope with this issue and simultaneously guarantee the legacy receiver against any impact is therefore a critical problem.

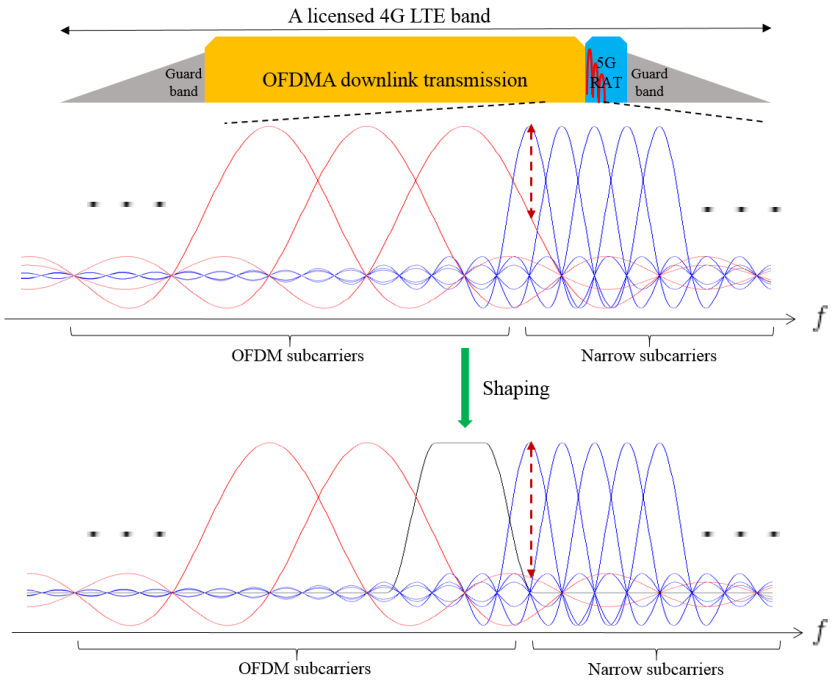

Figure 1: Illustration of the spectrum shaping for an LTE downlink band sharing with 5GRAT

1.1 Contributions

We accordingly propose exploiting the technique of spectrum shaping in order to meet the demand of heterogeneous LTE downlink spectrum access. The idea is to shape the "sinc" representation of the orthogonal frequency division multiplexing (OFDM) subcarrier near the narrow subcarriers into the "raised-cosine frequency response" representation so that the the undesired sidelobe impairment on 5GRAT can be effectively mitigated as indicated in Figure 1. To this end, we apply the modulation format of generalized frequency division multiplexing (GFDM) technology featuring low out-of-band emission (OOBE)[1] [9] to the corresponding OFDM subcarriers. We call this technique "embedded-GFDM" since it is like transplanting the GFDM system to the OFDM system. The proposed scheme warrants no impact on the signal detection of legacy receivers and gains much more spectral efficiency compared to guard band utilization. The proposed spectrum shaping method can also be applied to the realization of inter-operator spectrum sharing [10], where two adjacent bands governed by two operators utilize different subcarrier spacings with synchronization mismatch.

2 OFDM-Based Transceiver Structure

The transceiver architecture of the two-user downlink OFDM system can be represented by the building blocks as shown in Figure 2. The detailed notations and mathematical expressions of this system model can be found in [11]. The related background of such filter bank transceiver can be also found in [12].

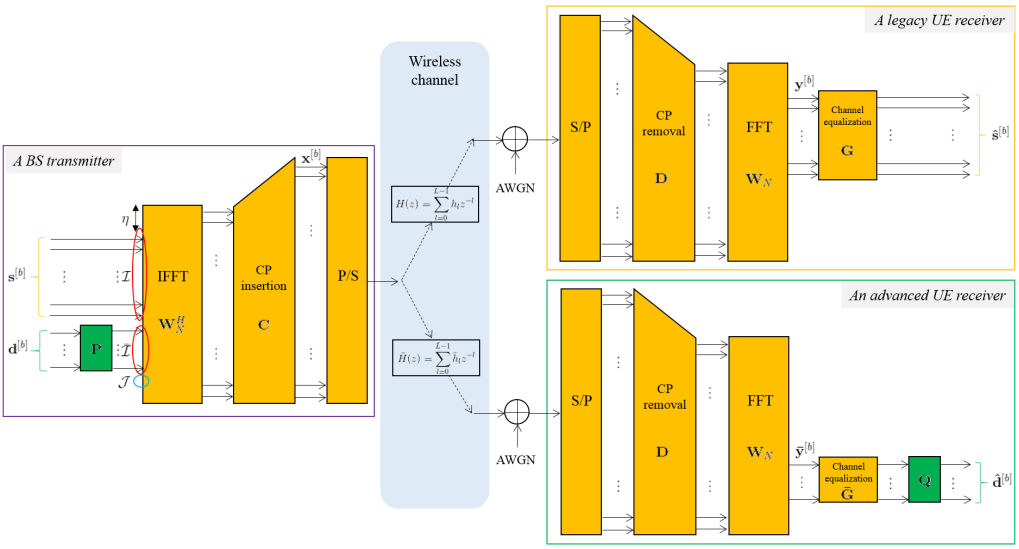

Figure 2: An OFDM-based transceiver architecture in which the precoder $\mathbf{P}$ is to be designed.

A profile of the fragmented spectrum assignment is illustrated in Figure 3, where η is the starting index, ψ is the d.c. subcarrier index, $\mathcal{I}$ is the set of OFDMA subcarrier indices, $\bar{\mathcal{I}}$ is the set of D dedicated subcarrier indices, and $\mathcal{J}$ is the set of indices corresponding to the J subcarriers whose frequency range is reserved for 5GRAT. We call the frequency range of the subcarriers indexed by $\bar{\mathcal{I}}$ a bridging band (BB), since it acts like a bridge between the legacy user and the new user adopting 5GRAT. The other two bands used for the legacy downlink transmission and the new applications are referred to as the legacy band (LB) and the reservation band (RB), respectively.

[1]Here OOBE is defined to be the leakage imposed on the band outside the occupied subcarriers of one user.

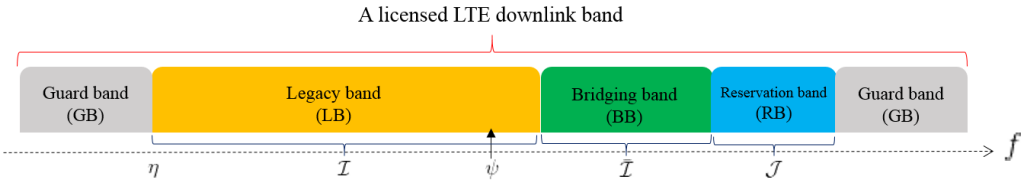

Figure 3: Fragmented spectrum assignment in a licensed LTE downlink band.

2.1 Precoder Design for Spectrum Shaping

Our goal is to enable heterogeneous LTE downlink spectrum access with high spectral efficiency. We intend to design an OFDM-compatible precoder $\mathbf{P}$ serving as a new transmission scheme in the BB and also functioning as spectrum shaping such that the OFDMA sidelobe leakage imposed on the RB can be mitigated efficiently.

To evaluate the achievable performance, power spectral density (PSD) is chosen as the metric. According to [13], the PSD of the analog baseband signal is given as

$$P(f) \quad = \quad \lim_{T\to\infty}\left(\frac{1}{T}\mathbb{E}\left\{|X_T(f)|^2\right\}\right), \tag{1}$$

where $X_T(f) = \mathbb{F}\left\{x_T(t)\right\}$ and $x_T(t)$ is the concatenation of B modulated blocks (i.e., $\mathbf{x}^{[b]}$, $b = 0, 1, \cdots, B-1$) within the time interval $(-T/2, T/2)$. Let $\mathcal{F}_{\text{RB}}$ denote the frequency range of the RB. The problem is therefore formulated as

$$\text{Find } \mathbf{P} \text{ s.t. } P(f)|_{\text{dB}} \leq \lambda, \;\; f \in \mathcal{F}_{\text{RB}}, \tag{2}$$

where λ in decibel (dB) indicates the threshold of the spectral leakage for the downlink transmission in the LB and BB. The value of λ can be determined according to the radio frequency (RF) requirement defined in the specification.

3 Embedded-GFDM

To tackle the problem given in Equation (2), we introduce an idea of spectrum shaping that embeds a block-based modulation featuring low OOBE in the OFDM modulation corresponding to the BB, while keeping the legacy transmission in the LB and alleviating the legacy sidelobe interference imposed on the RB. The transmission scheme in the BB is thus attributed to the embedded block-based modulator, which functions as a time-domain processing. The embedding process can be performed by adopting a discrete Fourier transform (DFT) served as an interface between the block-based modulation and the OFDM modulation.

In this document, the block-based modulation to be embedded with respect to the BB is chosen as GFDM, which is a widely known technology that exploits the property of circularly shifting a prototype pulse in both time and frequency domain to perform individual widened-subcarrier filtering for OOBE reduction [9], [14]-[16]. Figure 4 depicts a time-frequency paradigm of adopting embedded-GFDM when the RB is used for 5GRAT. The precoding matrix corresponding to the BB is given by

$$\mathbf{P} = \mathbf{W}_D\mathbf{A}, \tag{3}$$

where $\mathbf{W}_D$ and $\mathbf{A}$ denote a D-point DFT matrix and a GFDM modulation matrix, respectively. Note that embedded-GFDM inherits low OOBE characterization of GFDM when preventing steep change between two block transmissions and sharp variation of the first subcarrier.

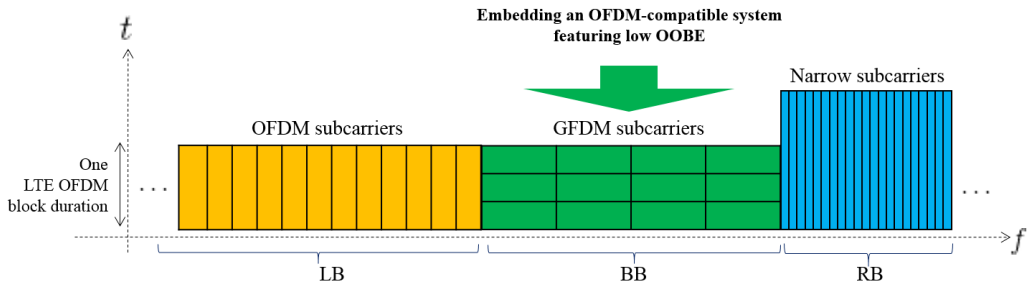

Figure 4: A time-frequency paradigm of adopting embedded-GFDM.

4 Simulation Results

4.1 Simulation Setup

The simulation parameters corresponding to the current LTE specification [19] are listed in Table 1. The allocation of LB, BB, and RB is in accordance with the subcarrier indices in $\mathcal{I}$, $\bar{\mathcal{I}}$, and $\mathcal{J}$ as shown in Figure 3. For the setting of the embedded-GFDM system in the BB, the chosen parameters are listed in Table 2. The processes of synchronization and channel estimation are assumed to be perfect.

Table 1: LTE OFDM system parameters.

Parameter	**Notation**	**Value**
Sampling rate		15.36MHz
Channel bandwidth		10MHz
OFDM subcarrier spacing		15kHz
FFT size	N	1024
CP length	N_{cp}	72
d.c. subcarrier index	ψ	512
Number of one-side null subcarriers	η	212
Number of the OFDMA subcarriers	S	444
Number of the dedicated subcarriers	D	144
Number of the reserved subcarriers	J	12
Modulation scheme		16QAM
Multipath channel model		EPA
Doppler shift		0

Table 2: Embedded-GFDM parameters.

Parameter	**Notation**	**Value**
Number of subcarriers	K	9
Number of sub-blocks	M	16
Number of guard subcarriers	K_{g}	1 $(k = 0)$
Number of guard sub-blocks	M_{g}	2 $(m = 0, M - 1)$
Number of null components	N_{nc}	32
Prototype filter	$\mathbf{a}_{0,0}$	Raised-cosine filter
Roll-off factor	α	0.8
Decoder	$\mathbf{Q}$	$\mathbf{P}^{-1}$

4.2 PSD Evaluation

We first evaluate the PSD performance only for the downlink transmission in the BB (i.e., $S = 0$). In Figure 5, it can be found that the embedded-GFDM waveform inherits low OOBE characterization of the GFDM waveform with one guard subcarrier and two guard sub-blocks. In this case, the transmission efficiency γ is 77.78%. Compare to the use of OFDMA with the same number of null subcarriers ($N_{\text{nc}} = 32$), the proposed waveform evidently achieves larger sidelobe attenuation.

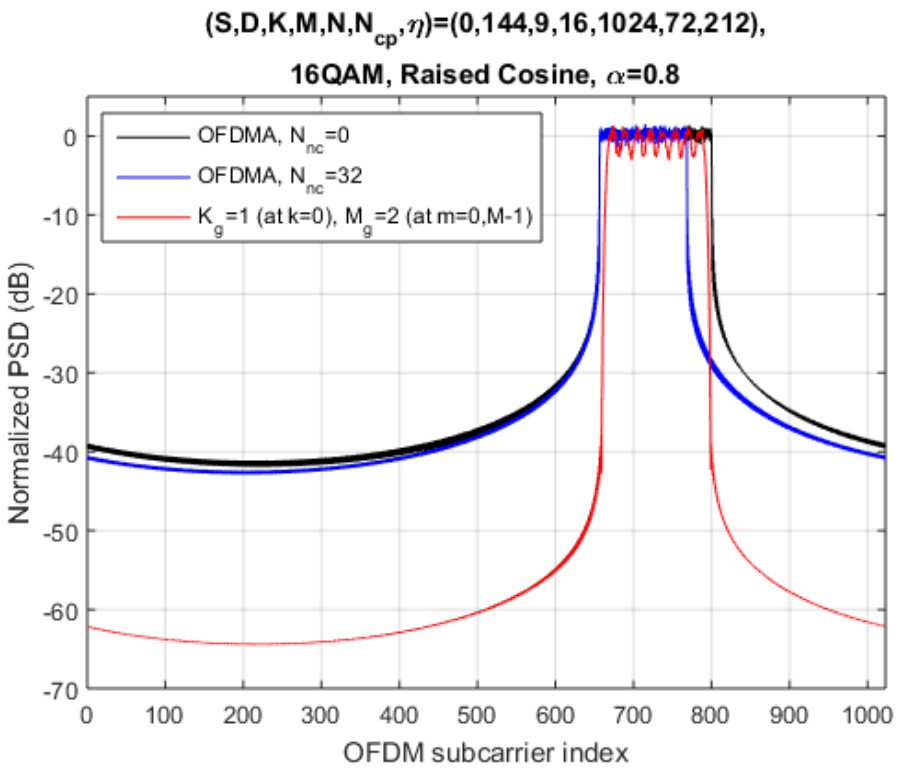

Figure 5: Low OOBE achieved by embedded-GFDM with $K_{\text{g}} = 1$ and $M_{\text{g}} = 2$ for the downlink transmission in the BB.

Then, we consider joint downlink transmission of the legacy OFDMA and the embedded-GFDM in the LB and the BB, respectively. As shown in Figure 6, observed from $\mathcal{J} = \{801, 802, \cdots, 812\}$, the embedded-GFDM corresponding to the BB acts as a functionality of spectrum shaping to prevent the adjacent RB used for 5GRAT from receiving severe sidelobe interference caused by the legacy OFDMA transmission. Moreover, the level of spectrum shaping can be enhanced as the frequency range of the BB increases as revealed in Figure 7.

The operation of spectrum shaping can satisfy the OOBE criterion stated in Equation (2). For $\lambda = -34$dB, as shown in Figure 6, the OFDMA waveform requires 144 null subcarriers. In the proposed scheme, equivalently, only 32 null subcarriers are needed. It obviously gains much more spectral efficiency for heterogeneous LTE downlink spectrum access. Note that the legacy sidelobe leakage level can be found in [20] and the value of λ shall be determined according to future 5G RF requirements.

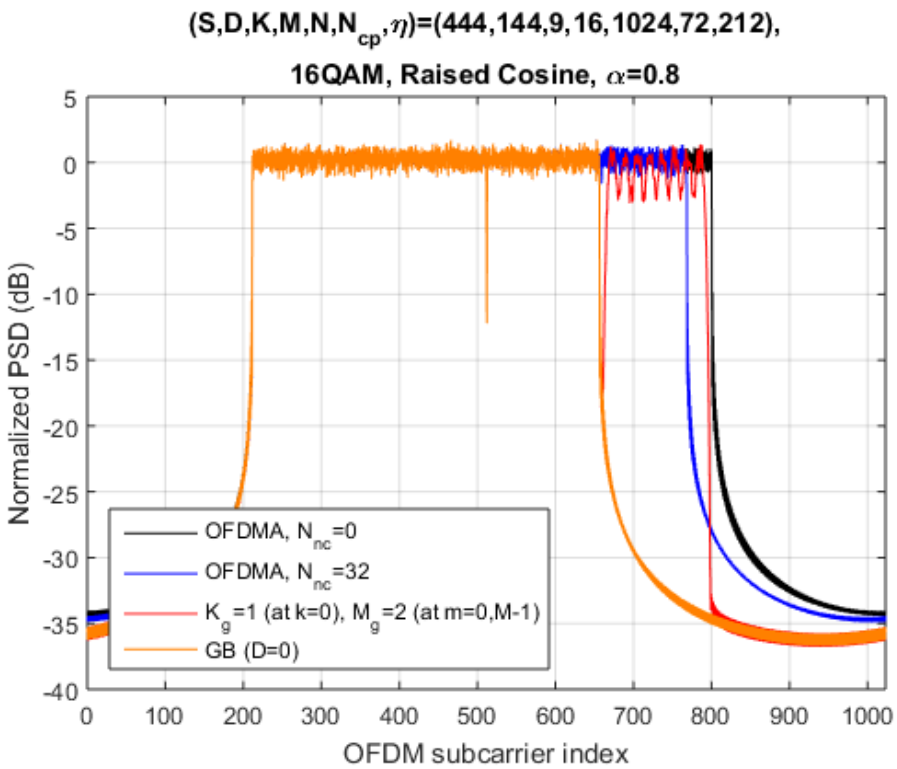

Figure 6: Embedded-GFDM functioning as the spectrum shaping of legacy OFDMA transmission gaining much more spectral efficiency compared to GB utilization.

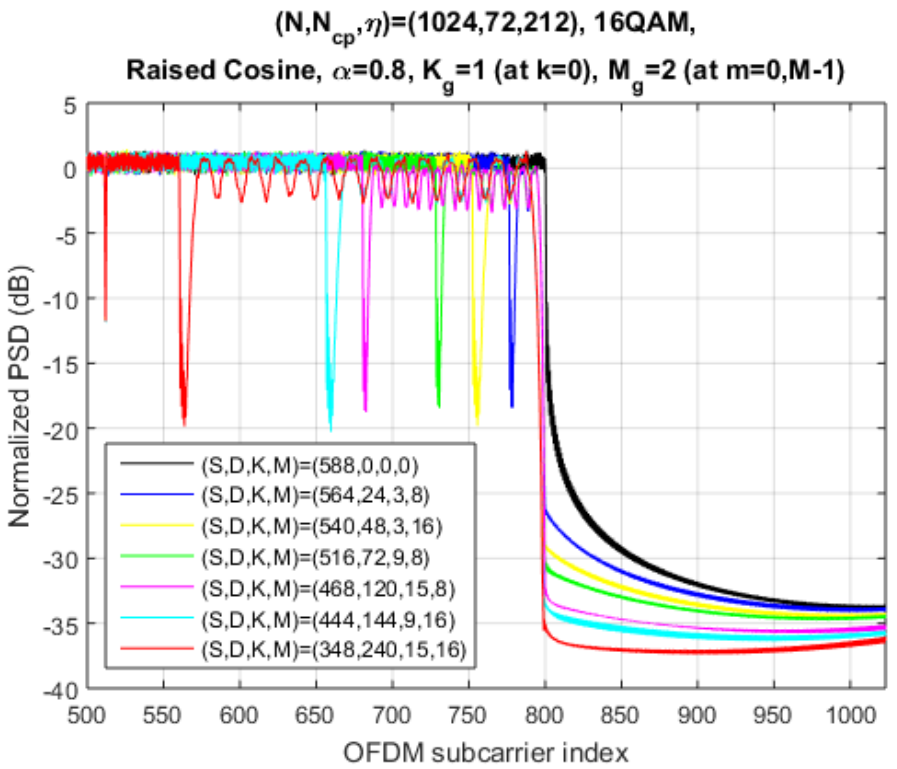

Figure 7: Illustration of the flexibility of embedded-GFDM that the level of spectrum shaping depends on the frequency range of the BB.

4.3 PAPR Evaluation

For transmitter implementation, PAPR is a critical factor that highly correlates with the efficiency of the power amplifier [21]. PAPR can be evaluated by showing its complementary cumulative distribution function (CCDF) defined as

$$\text{CCDF} = 1 - \Pr\left\{\text{PAPR} \leq \text{PAPR}_0\right\}, \tag{4}$$

where $\Pr\left\{\text{PAPR} \leq \text{PAPR}_0\right\}$ indicates the probability of PAPR that does not exceed a given threshold denoted by PAPR_0. As shown in Figure 8, the PAPR performance of using embedded-GFDM is very similar to the legacy OFDMA transmission. Hence, no additional processing of PAPR reduction is needed for the legacy base station (BS).

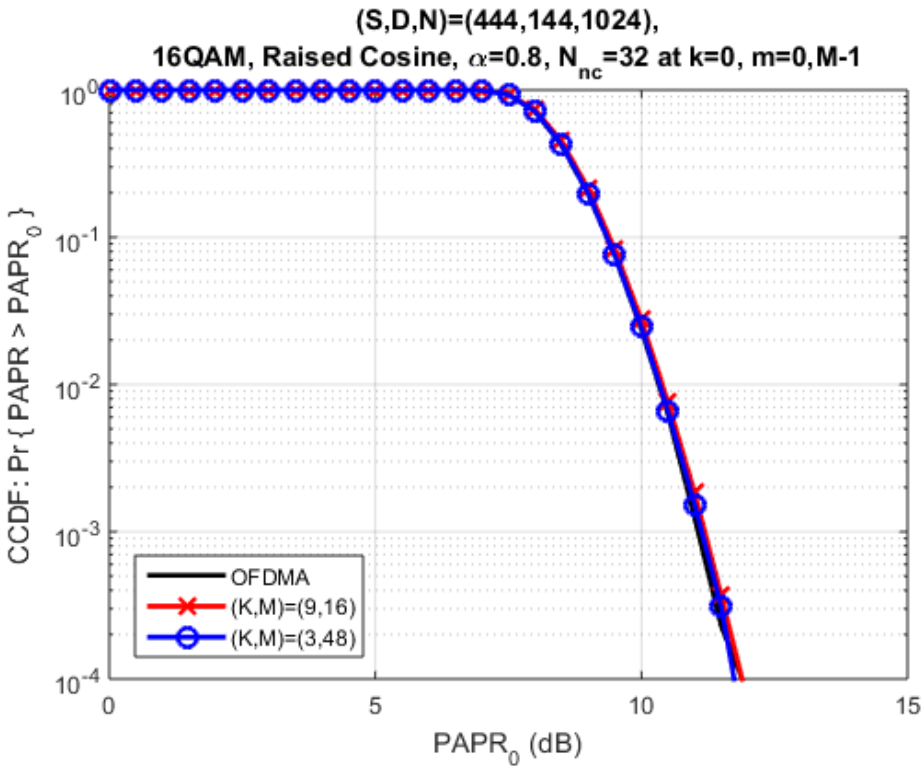

Figure 8: No additional PAPR burden for BS when introducing embedded-GFDM to the BB.

4.4 Unocoded BER Evaluation

The BER performance is analyzed to verify the feasibility of the proposed embedded-GFDM. Here the legacy UE and the advanced UE are assumed to have the same noise variance and receive the downlink signals via the same channel model (EPA). As shown in Figure 9, compared with the legacy UE, the advanced UE has about 2dB performance degradation given a fixed BER (e.g., 10^{-2}). The reason is that the ZF decoder $\mathbf{Q}$ results in the noise enhancement. The legacy UE remains the same performance because of the preservation of orthogonality among the subcarriers indexed by $\mathcal{I}$ and $\bar{\mathcal{I}}$.

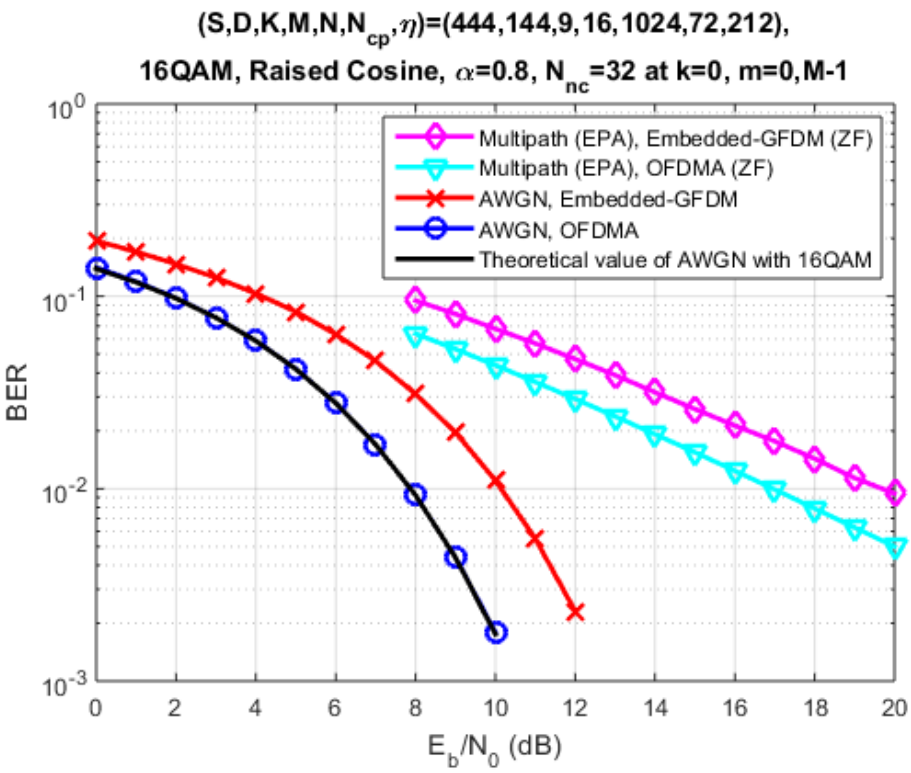

Figure 9: No performance degradation for the legacy UE due to orthogonality preservation and 2dB performance gap for the advanced UE due to noise enhancement.

5 Summary

The idea of using embedded-GFDM in the bridging band is proposed to facilitate heterogeneous LTE downlink spectrum access with high spectral efficiency. Based on the analysis and the evaluations in this document, we summarize the observations and then make one proposal as follows:

Observation 1: *Embedded-GFDM functioning as spectrum shaping of legacy OFDMA transmission gains much more spectral efficiency compared to guard band utilization to prevent significant legacy sidelobe interference imposed on the reservation band.*

Observation 2: *With embedded-GFDM at the BS transmitter, legacy UE receivers remain the same signal detection performance as usual because of orthogonality preservation among users.*

Observation 3: *To enable the coexistence of LTE and NR in current licensed bands, the modification of legacy global downlink pilot strategies would be considered.*

Observation 4: *Embedded-GFDM itself can be regarded as a new waveform characterized by its precoder flexibility*[2]*, while the corresponding decoder is needed at the receiver.*

Proposal 1: *Embedded-GFDM shall be further studied in order to facilitate the coexistence of LTE and NR in the current licensed bands below 6 GHz.*

[2]We also call it CPS-OFDM, whose details can be found in [22]-[23]

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