

NB-IoT NTN Band-Edge Attenuation/EVM Tradeoff with Real-System Verification

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Abstract— In 3GPP 5G narrowband Internet-of-Things (NB-IoT) non-terrestrial networks (NTNs) based on a satellite, a relayed gNodeB (gNB) base station orthogonal frequency-division multiple access (OFDMA) signal is required to meet the highly strict band-edge attenuation constraint and simultaneously maintain acceptable error vector magnitude (EVM) performance. Although these seem to be two conflicting goals, we pursued a favourable tradeoff between gNB band-edge attenuation and EVM by designing a two-stage interpolated finite-impulse response (IFIR) filter. We first follow the 3GPP NB-IoT specification to generate a standard gNB signal, and then we designed and optimized the filter for a relayed gNB signal and simulated its effectiveness. The proposed gNB TX design was not only verified through simulation, but also practically verified by the commercial vector signal analyser (VSA). Hence, this work can be realistically applied to standard NB-IoT signals, making it a critical enabling technology for converting the original NB-IoT TN to NTN and can help NTN operators to flexibly allocate channels, improve overall spectrum efficiency, and avoid waste of spectrum resources.

Keywords— Narrowband Internet-of-Things, Non-Terrestrial Network, Satellite, Geostationary Orbit, Spectral Edge, Error Vector Magnitude, Real-system

I. INTRODUCTION

Over the last three decades, wireless terrestrial networks (TNs) have spread across the globe. However, some remote areas, such as mountains and oceans, remain difficult to cover by TNs. Therefore, non-terrestrial networks (NTNs) are a promising alternative to TNs for global coverage extension and are expected to play a key role in the beyond-5G or 6G era. In this study, we investigated the expected shift from the current narrowband Internet of Things (NB-IoT) over TNs to the emerging NB-IoT over NTNs. We also investigated some key technological issues from a physical layer perspective.

Currently, NB-IoT is regarded as a 5G massive machine-type communication (mMTC) technology [1], [2]. To further develop NB-IoT technology, in August 2020, MediaTek (MTK) also announced that they had successfully conducted the first experiment of NB-IoT over NTNs by using the Inmarsat Alphasat geostationary orbit (GEO) satellite and Institute for Information Industry (III) gNB [3]. Using the standardization plan of 5G over NTNs, several working

groups are currently investigating the NB-IoT NTN architecture with satellites [4], [5]. In addition, the 3GPP is expected to release the R17 specification in 2022, which is predicted to specify the NB-IoT over NTN standard to provide access to user equipment (UE) on Earth. In this study, we mainly focus on the NTN scenario A which employs GEO located at 35 786 km above the equator to relay the NB-IoT signals transparently. As compared to the low-Earth orbit (LEO) NTN scenario B and C [6], one major advantage of NTN scenario A is the negligible Doppler effect. Moreover, only three GEO satellites are required to achieve global coverage. Figure 1 shows all the spot beam footprints of three Inmarsat GEO satellites to cover Americas, Europe/Middle East/Africa (EMEA), and Asia-Pacific areas, respectively [7]. Hence, the GEO-based NTNs can be deployed more quickly and much easier than their LEO-based counterparts [8]–[10].

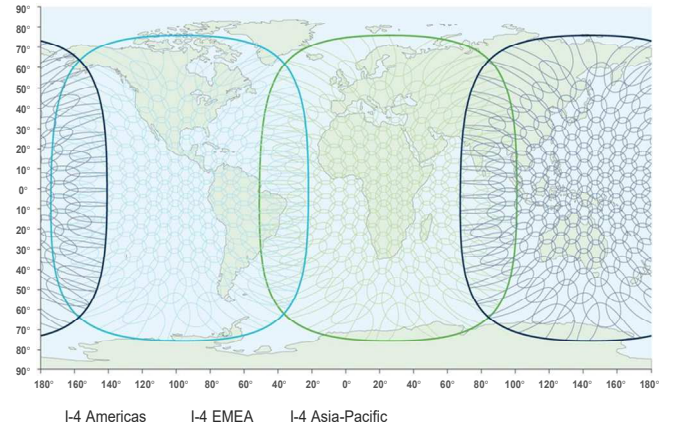


Figure 1. The spot beam footprints of three Inmarsat GEO satellites for global coverage [7]

However, the GEO spectrum resources are very scarcity, hence, the GEO operator imposes very strict spectral band edge attenuation regulation such as to facilitate frequency reuse among multiple beams and to minimize the co-channel interference. Under NTN scenario A, the satellite operators would often require that the relayed signal should confine its spectrum very compactly by attaining more than 60 dB attenuation at the allocated band edge to reduce its

interference to adjacent channels so that the operator can flexibly allocate frequency channels and improve overall spectrum efficiency, thereby avoiding the waste of spectrum resources.

To suppress the spectral edge leakage of a gNB-transmitted orthogonal frequency-division multiple access (OFDMA) signal, various filtering techniques with different structures, such as analog and digital filters, can be used. However, an adequate filtering approach should not only have a frequency response (FR) with a highly sharp roll-off but also maintain acceptable outer subcarrier error vector magnitude (EVM) performance for the filtered gNB OFDMA signal. Otherwise, the system link performance will suffer from severe degradation as a result of an inadequate filter design, especially the narrower the bandwidth of the signal, the greater the EVM rise, because the proportion of the subcarriers affected in the band edge to the overall bandwidth is higher, the overall EVM will be degraded more severely [11]. So that a tradeoff is required between EVM performance and spectral leakage.

Given the design criteria highlighted earlier, we reference literature [12], design a two-stage interpolated finite-impulse response (IFIR) filtering approach for NB-IoT gNB signal. It can not only effectively suppress the spectrum edge, but also maintain an acceptable EVM performance. Thus, making it a critical enabling technology for converting the original NB-IoT TN to NTN.

This paper is organized as follows. In Section II, we introduce the 3GPP NTN scenario A for relaying gNB OFDMA signals and address the gNB filtering problem with the spectral edge/EVM tradeoff. In Section III, the basics of IFIR filter design is reviewed. In Section IV, the specific gNB IFIR filter is designed and evaluated for different filter lengths and coefficient optimization techniques, and in the end a 128-tap IFIR filter is obtained. In Section V, the concluding remarks are made.

II. GEO NTN AND NB-IOT BAND-EDGE PROBLEM

A. 3GPP NTN Scenario A

The NB-IoT NTN scenario considered in this study was the 3GPP NTN scenario A. As shown in Figure 2, the UE directly communicates with the GEO (also called the direct access mode in NTNs), and the gNB signal is relayed through the ground station gateway and GEO to the UE. In the scenario A, the GEO serves as a sky transponder to transparently relay the gNB and UE signals.

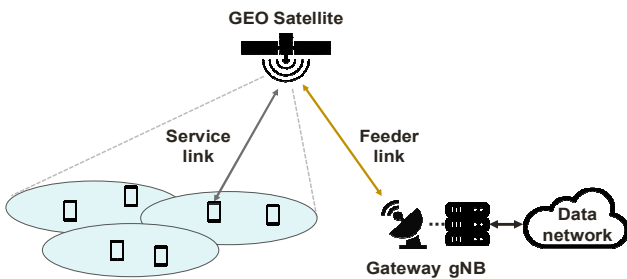


Figure 2. Transparent GEO satellite scenario (3GPP NTN scenario A)

B. gNB OFDMA Signal Structure

Overall, the NB-IoT transmission scheme is the same as that of 4G Long-Term Evolution (LTE), which uses OFDMA for the downlink (DL) signal. Figure 3 shows the NB-IoT DL signal frame structure, in which one radio frame consists of 10 subframes with a duration of 1 ms and each subframe consists of 14 OFDM symbols. For each OFDM symbol, 12 subcarriers spaced by 15 kHz can carry either a Zadoff-Chu synchronization signal (NPSS/NSSS) or a system/user information data channel (NPBCH/NPDCCH/NPDSCH) in QPSK modulation. Hence, the nominal DL signal bandwidth is 180 kHz, which coincides with that of the LTE resource block, and the baseband sampling rate of the generated I/Q signal samples is $F_s = 1.92$ Msps [13]. In order to conform to the real application scenario, this paper will follow the 3GPP specification to generate the above gNB signals/channel for this research.

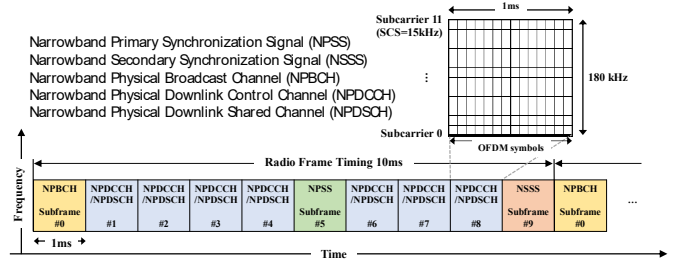


Figure 3. NB-IoT DL frame structure

C. Filtering Challenge with Band-Edge Attenuation/EVM Tradeoff

During the conformance test of the 3GPP for the terrestrial NB-IoT DL signal, the adjacent channel leakage ratio (ACLR) of the signal at 300 kHz from its center frequency (CF) was required to be better than 40 dB for terrestrial communication [14]. Therefore, the NB-IoT gNB typically applies low-pass digital filtering to the original I/Q signal to suppress its baseband sidelobes. However, such an ACLR requirement for TNs is too loose for NB-IoT NTNs.

In the NTN scenario A, to avoid interference with other GEO commercial services, the power spectrum of the relayed OFDMA signal should be strictly limited to be within a bandwidth of 200 kHz, which results in a serious challenge on the gNB side. For example, some GEO operators specify that the band-edge attenuation at 100 kHz from the center frequency should be larger than 60 dB. Therefore, the gNB for NTN scenario A requires more sophisticated output filtering before it transmit signal is sent to the gateway and GEO.

In addition to the band-edge suppression challenge that GEO operators face, another vital requirement should be considered by network operators, whose primary goal is to maintain an acceptable link performance. During the 3GPP conformance test, transmit signal quality was evaluated in terms of the EVM of the modulation constellation. For example, for QPSK constellation to be faithfully received, the EVM should be less than 17.5% [14]. Due to the long trail FIR filtering, it will introduce both the inter symbol interference (ISI) and inter carrier interference (ICI) in the

NB-IoT OFDM signals, and these can be reflected in the EVM figure. Hence, the filtered signal may exhibit severe EVM degradation at its outermost subcarrier as a result of spectral edge suppression. In this study, we addressed this challenge to achieve an implementable filter design with a favourable tradeoff between band-edge suppression and EVM performance.

Figure 4 shows a simulation of the band-edge attenuation, band-edge EVM results for the original and two filtered NB-IoT OFDMA baseband signals, and Table 1 summarizes the comparison results. Here, two 64-tap equiripple finite-impulse response (FIR) filters were designed and are denoted as FIR#1 and FIR#2, with different transition bands $[F_{pass} F_{stop}]$ as $[90 \ 120]$ kHz and $[90 \ 100]$ kHz, respectively. Shown by the results, with the equiripple FIR response becoming sharper, the outermost subcarrier EVM deteriorated, indicating that traditional filters cannot achieve the band-edge attenuation/EVM tradeoff. These results indicate that traditional filtering is insufficient to meet the challenge highlighted earlier.

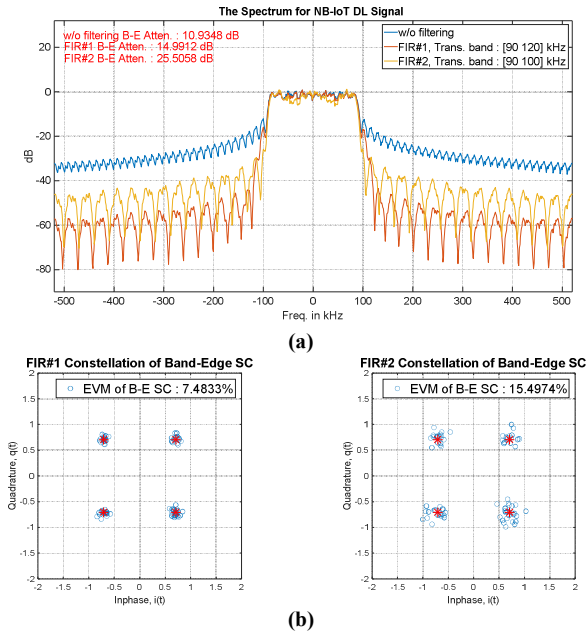


Figure 4. (a) band-edge attenuation with three different filtering cases, (b) band-edge EVM results with FIR#1 and FIR#2

TABLE 1. COMPARISON OF THREE FILTERING RESULTS

Filtering Cases	Band-Edge Attenuation (dB) @100 kHz	Band-Edge SC EVM: (%)
w/o Filtering	10.934	0.00
64-Tap FIR#1	14.991	7.483
64-Tap FIR#2	25.505	15.49

In the following sections, we propose using the IFIR filtering technique to meet both the band-edge attenuation and EVM requirements. This can allow for development of a feasible and practical gNB filter for NTN scenario A.

III. TWO-STAGE IFIR FILTERING PRINCIPLE

Basically, the IFIR approach involves designing two cascaded low-pass filters (LPFs). The first-stage filter is constructed by up-sampling (or interpolation with inserted zeros) the impulse response (IR) of a prototype filter (PF). Hence, the frequency response (FR) of the first-stage filter will be the replicated and compressed FR of PF. This makes the first-stage filter serve as the so called band-edge filter (BF) with sharp roll-off. Then the second-stage filter in the IFIR design is used to remove the replicated FR images except the low-pass part around the DC, and is thus called the masking filter (MF). Generally, the composite response of the two-stage IFIR filter can achieve a highly sharp roll-off, rendering it highly suitable for GEO specifications in band-edge attenuation. Figure 5 shows the IFIR two-stage filtering structure.

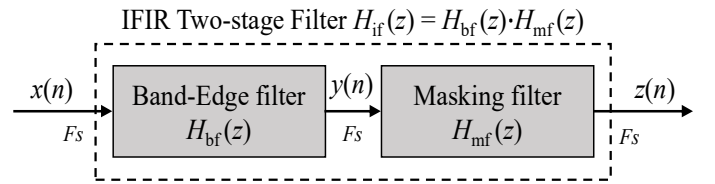


Figure 5. Structure of an IFIR filter

In the following, we concisely explain the IFIR design principle. Starting with a chosen prototype linear-phase FIR LPF, let its z transfer function be expressed as follows:

$$H_{pf}(z) = \sum_{k=0}^{N-1} h_{pf}(k)z^{-k} \quad (1)$$

where $h_{pf}(k)$ denotes the prototype filter's IR of length N . Then interpolating $h_{pf}(k)$ by an up-sampling factor M , the first-stage BF IR $h_{bf}(k)$ for band-edge shaping is obtained, in which the interpolation simply involves inserting $M-1$ zeros between each consecutive coefficient of $h_{pf}(k)$. Hence, the z transfer function of the first-stage band-edge filter is as follows:

$$H_{bf}(z) = \sum_{l=0}^{MN-1} h_{bf}(l)z^{-l} = \sum_{k=0}^{N-1} h_{pf}(k)z^{-kM} \quad (2)$$

where $h_{bf}(l) = h_{pf}(k)$ for $l=kM$ and $h_{bf}(l) = 0$ elsewhere. Thus, if the input sampling rate is $F_s = 1.92$ Msps, then by letting $z = e^{(j2\pi f/F_s)}$, we can obtain the BF's FR $H_{bf}(e^{j2\pi f/F_s})$, which simply denotes the replicated images of the original PF's FR $H_{pf}(e^{j2\pi f/F_s})$ at integer multiples of F_s/M Hz. Figure 6 shows the relationship between the two responses $H_{bf}(e^{j2\pi f/F_s})$ and $H_{pf}(e^{j2\pi f/F_s})$ at $M = 4$. Hence, the band-edge roll-off of $H_{bf}(e^{j2\pi f/F_s})$ is four times sharper than that of $H_{pf}(e^{j2\pi f/F_s})$, hence the name band-edge filter. Finally, to remove the other images, a second-stage MF with a mild roll-off FR $H_{mf}(e^{j2\pi f/F_s})$ was designed, as shown in Figure 6. Finally, the resultant IFIR filter's FR is given by

$$H_{if}(e^{j2\pi f/F_s}) = H_{bf}(e^{j2\pi f/F_s})H_{mf}(e^{j2\pi f/F_s}). \quad (3)$$

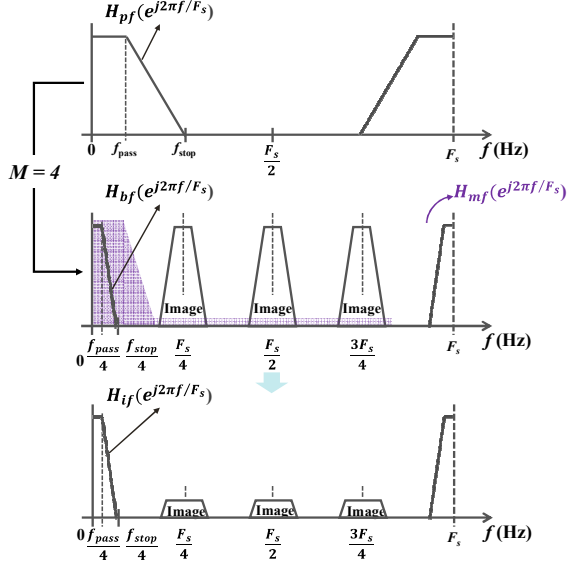


Figure 6. FRs of the prototype, band-edge, masking, and final two-stage IFIR filter

IV. DESIGNING THE IFIR FILTER FOR NB-IOT GNB

A. 64-Tap Least-Squares Prototype Filter Design

The prototype FIR filter is crucial in the IFIR filtering approach. To begin the design, we chose an IFIR up-sampling factor $M = 4$ and a prototype filter length $N = 64$. Because FIR filters with a least-squares (LS) design can form sharper band-edges than those formed by Parks–McClellan equiripple filters, we first designed a 64-tap FIR filter by using the function “firls” in the MATLAB Filter Design Toolbox, in which the transition band was set as $[F_{pass} F_{stop}] = [355 \ 400]$ kHz.

B. 128-Tap Prototype Filter Design with Multi-Objective and Advanced Optimization Techniques

Although the above LS PF with 64 taps can form a null at 400 kHz, its passband edge at 455 kHz may be insufficient to maintain an acceptable edge EVM performance. Therefore, we designed a 128-tap prototype filter with a sharper edge response and narrower transition band similar to that in [15] by integrating three error fitness objectives for (1) stopband attenuation, (2) the transition band ([360 400] kHz), and (3) passband ripple. Then the MATLAB global optimization toolbox was employed to solve the associated multi-objective minimization problem in terms of particle swarm optimization and differential evolution methods. Finally, after some trials, we obtained an optimized 128-tap FIR prototype filter.

Compared with the former 64-tap LS FIR filter, the 128-tap filter had a sharper band-edge response, narrower transition band, lower stopband attenuation, and much smaller passband ripple.

C. MF Design and Overall IFIR Responses

After designing the prototype filter responses, we used the up-sampling factor $M = 4$ to implement the first-stage IFIR band-edge filter. To suppress the unwanted images of the band-edge filter, an LS MF is then designed with the

following specifications: (1) filter length = 64 taps, (2) transition band = [100 200] kHz, and (3) ratio of stopband to passband weight = 100.

Using the two candidate prototype filters (i.e., PF#1 with 64 taps and PF#2 with 128 taps), we constructed two band-edge filters BF#1 and BF#2 by interpolating zeros. Finally, by cascading the 64-tap MF after BF#1 and BF#2, we obtained two candidate IFIR filters as follows:

- IFIR#1: BF#1 (based on the 64-tap PF#1) + MF
- IFIR#2: BF#2 (based on the 128-tap PF#2) + MF

D. Simulation of Band-Edge Attenuation and EVM

Computer simulations were used to evaluate the band-edge attenuation and EVM performance by passing a typical gNB OFDMA signal through the two previously described candidate IFIR designs, namely, IFIR#1 and IFIR#2. From the simulation results, one IFIR design was chosen for implementation on the SDR-based gNB. The following are the two criteria that we used to choose the IFIR: (C1) having simulated band-edge attenuation 60 dB, (C2) having a band-edge EVM $\leq 10\%$. Figures 8 and 9 show the band-edge attenuation and EVM simulation results. Another EVM result is presented in Figure 9, which was obtained by feeding the filtered I/Q data into the commercial vector signal analysis (VSA) Keysight 89600 software, and the results are compared in Table 2. Although IFIR#1 successfully met the C1 criterion, its edge EVM did not meet the C2 criterion (20.111%). By contrast, IFIR#2 successfully met both the C1 and C2 criteria. Furthermore, using IFIR#2 outperforms IFIR#1 according to the EVM analysis results. Therefore, IFIR#2 can not only suppress the band-edge spectrum, but also maintain acceptable EVM performance.

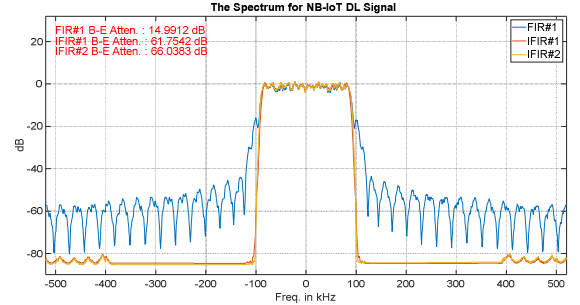


Figure 7. Band-edge attenuation of IFIR#1 and IFIR#2

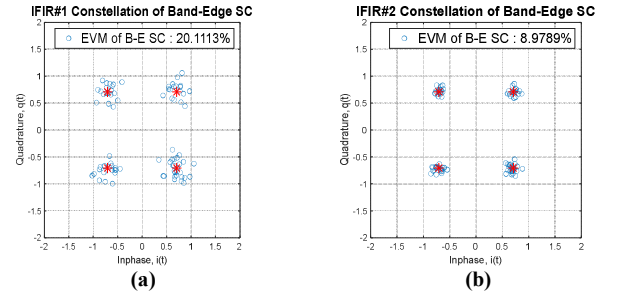


Figure 8. EVM simulation results of (a) IFIR#1, (b) IFIR#2

EVM	= 8.7894	%rms	EVM	= 4.1425	%rms
EVM Pk	= 39.746	%	EVM Pk	= 16.565	%
Data EVM	= 8.9209	%rms	Data EVM	= 4.2624	%rms
RS EVM	= 9.5289	%rms	RS EVM	= 3.8768	%rms
Channel Power	= 1.479	dBm	Channel Power	= 1.382	dBm
RS Tx. Power (Avg)	= -9.017	dBm	RS Tx. Power (Avg)	= -9.045	dBm
OFDM Sym. Tx. Power	= 1.844	dBm	OFDM Sym. Tx. Power	= 1.767	dBm
RS Rx. Power (Avg)	= -9.017	dBm	RS Rx. Power (Avg)	= -9.045	dBm
RSSI	= 1.772	dBm	RSSI	= 1.701	dBm
RS Rx. Quality	= -10.789	dB	RS Rx. Quality	= -10.746	dB

(a)

(b)

Figure 9. Keysight 89600 VSA software measurement results
(a) the average EVM for IFIR#1, (b) the average EVM for IFIR#2

TABLE 2. COMPUTER SIMULATION COMPARISON OF FILTERING RESULT

Filtering Cases	Band-Edge Attenuation: (dB)@100kHz	EVM	
		Band-Edge (%)	Average (%)
FIR#1	14.991	7.483	4.692
IFIR#1	61.754	20.113	8.789
IFIR#2	66.038	8.978	4.142

V. CONCLUSIONS

In this study, we addressed the practical problem of simultaneously satisfying both band-edge attenuation and EVM performance for NB-IoT gNB in the 3GPP NTN scenario A. Firstly, we are following 3GPP specification to generate standard NB-IoT gNB signal to compatible with real system implementation. Secondly, we used two-stage IFIR filtering approach to investigate whether a favourable tradeoff exists between the attenuation (C1) and EVM (C2) criteria. Finally, after designing and simulating numerous candidate IFIR filters, we selected IFIR#2 with an optimized 128-tap prototype filter as the final design, which not only can meet strict spectral band-edge attenuation for NTN but also maintain network operator requirements for link performance. Hence, we conclude that the proposed for the two-stage IFIR filter can successfully satisfy all the criteria and can implementation at standard NB-IoT system. Therefore, this study is a promising candidate for practical applications in NB-IoT over NTN.

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