A Practical Framework to Specify the Prototype Filters for the Analysis of Frequency Stacked Sub-bands

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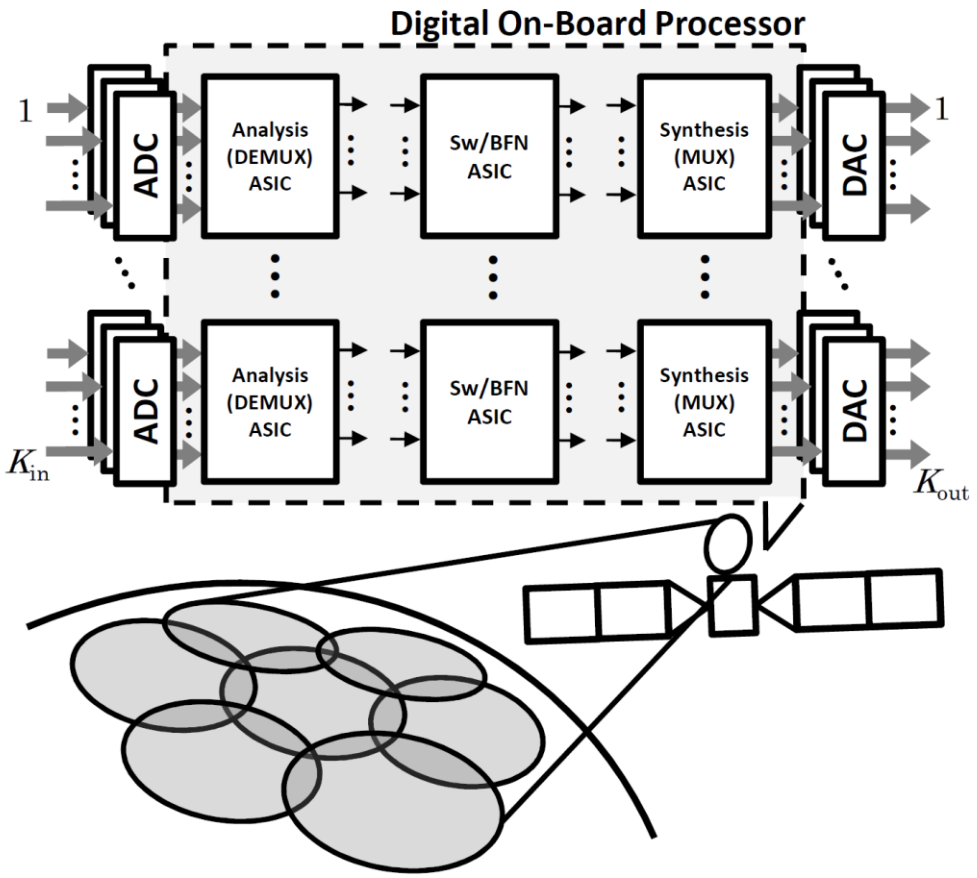
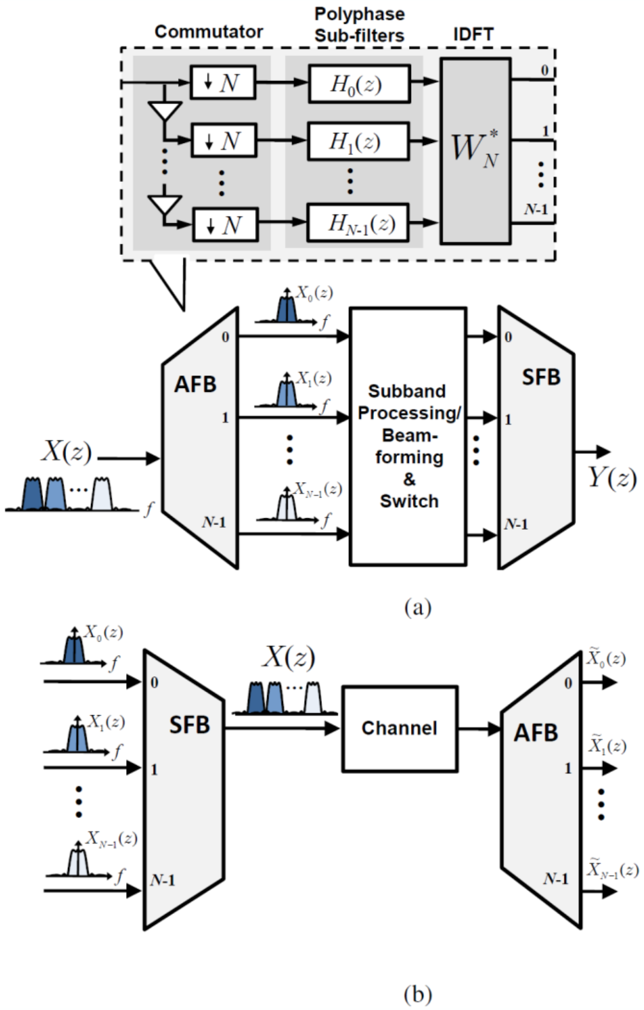
Digital OBP for Beamforming Satellites



A representation of a beamforming satellite generating multiple spot beams and equipped with a digital OBP. The digital OBP contains three sets of ASICs for the Analysis, routing and the Synthesis of the communication spectrum as well as delivering the switching and the beamforming operations.

- Beamforming satellites make it possible to easily realise frequency reuse. They provide flexibility and improved efficiency in the use of the available frequency spectrum.
- VHTS/UHTS, as well as satellites providing Mobile Satellite Services (MSS), are equipped with multiple antenna elements to facilitate beamforming both for the transmit and receive modes of operations.
- On-Board Processor (OBP) can deliver the channelisation and baseband processing functions of the communication spectrum.
- The tasks of a Transparent digital OBP are assigned to three sets of Application-Specific Integrated Circuits (ASICs) that are; (1) the Analysis (2) Switch/BeamForming Network and the (3) Synthesis.

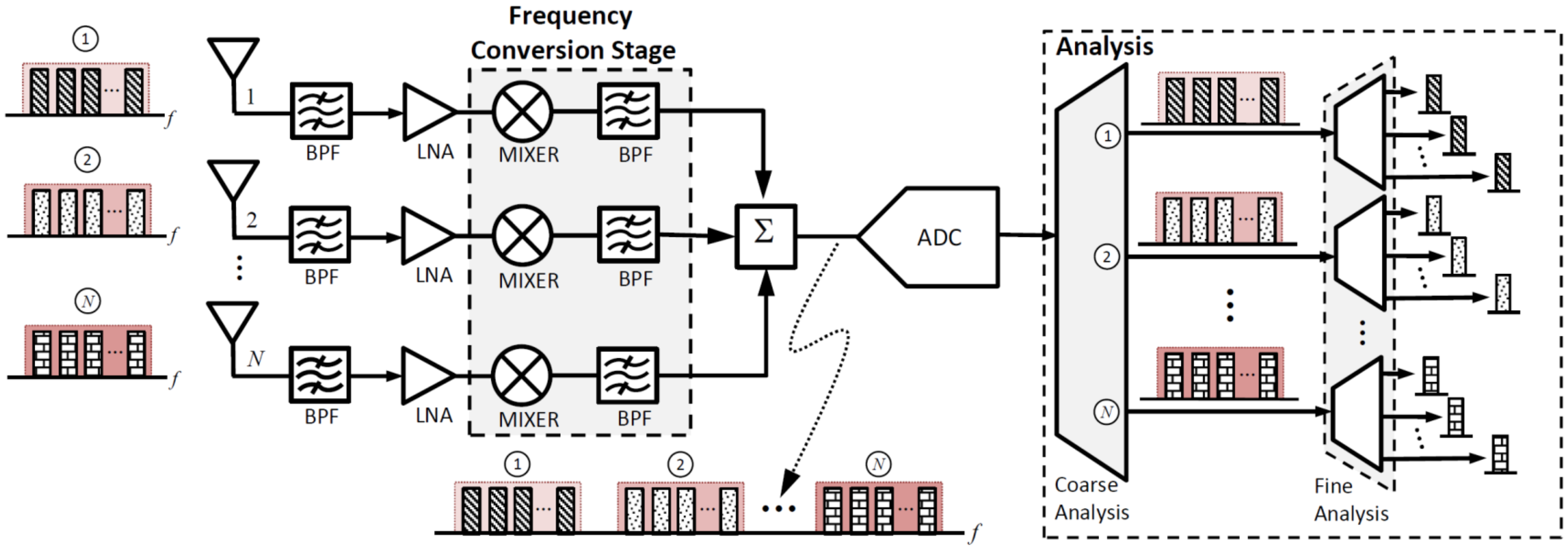
Digital OBP for Beamforming Satellites



(a) The Analysis Filter Bank (AFB) and the Synthesis Filter Bank (SFB) to analyse and synthesise a communication spectrum (b) The same can be achieved in the form of a Transmultiplexer,

- The Analysis ASICs are responsible for the division of the frequency modulated spectrum into multiple bands, while the reconstruction of the spectrum is delivered by the Synthesis ASICs.
- The cross-connections deployed across the Sw/BFN ASICs simultaneously give full routing flexibility as well as delivering the digital beamforming operations.
- To support the Analysis and Synthesis functions, a uniform modulated filter bank architecture can be used that is composed of;
  - a set of polyphase sub-filters, H_n (z), of a prototype filter and
  - Discrete Fourier Transform to modulate the prototype filter.

Frequency Stacking



- Because ASIC development times and costs are very high, in practice it is not viable to design a new ASIC specific to each mission. Increasing the applicability of a single development to a wider range of missions reduces the overall cost of On-Board Processor (OBP) for satellite telecommunications.
- A commonly proposed solution is to use different analog pre-processing to chop up wide signal bands or stack narrow ones in order to provide a common broadband digital interface. This figure shows an example scheme in which N elements are stacked using a combination of N pre-processing chains. This operation is known as "Frequency Stacking"

Prototype Filter Specifications

A FRAMEWORK TO SPECIFY THE LOWPASS PROTOTYPE FILTER TO THE ANALYSIS OF FREQUENCY-STACKED SUB-BANDS

Input f_s, f_o, f_c, ν, B *and* $N = 2 \times N_c$

1: $\rho = \lfloor \frac{\nu}{2} \rfloor$; s=sgn(2$\rho$-$\nu$+1/2)

2: ***for*** n = 1,…, $N/2$-1 ***do***

3: $\varphi_n = argmin_{\beta_n \in \mathbb{Z}^+} \left(\left| F_n - n\frac{f_s}{N} \right| \right)$

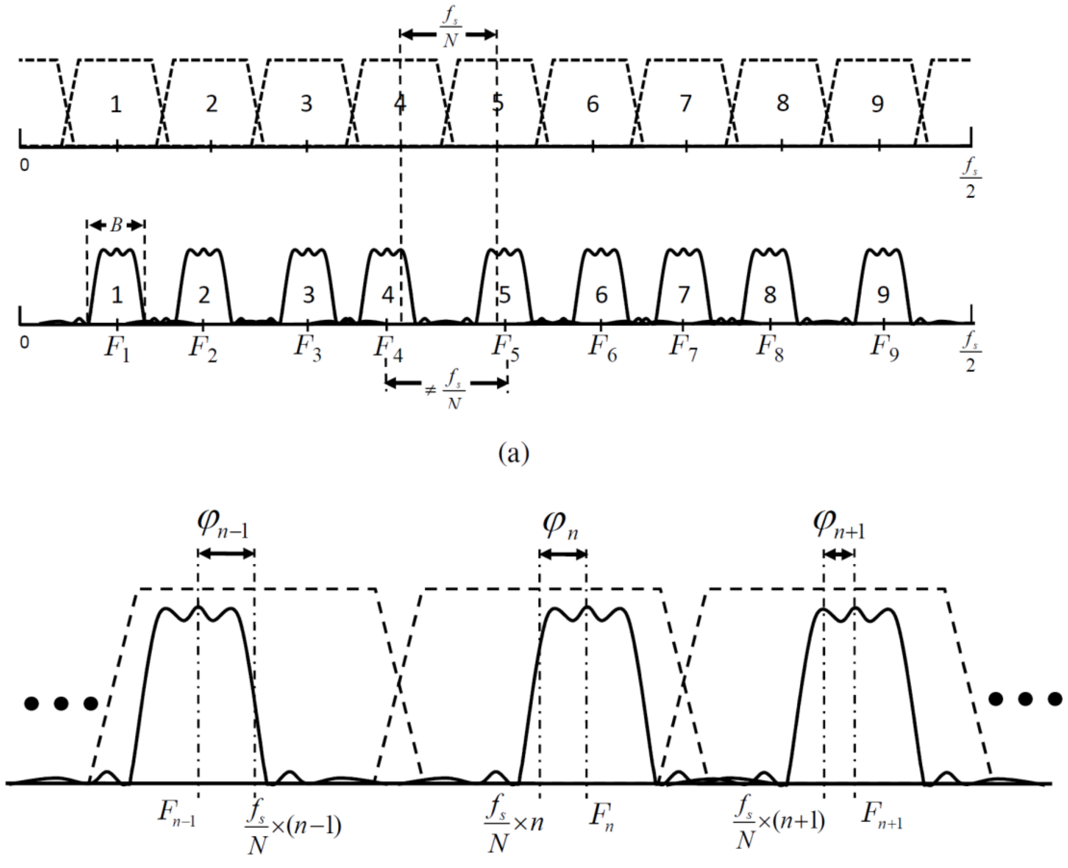
  where $F_n = s \times (\beta_n f_o - \ (f_c - \rho\ f_s))$

4: ***end***

5: $f_p = max\left\{ [\varphi_1, \varphi_2,\ \ldots,\ \varphi_{N/2-1}] \right\} + \frac{B}{2}$

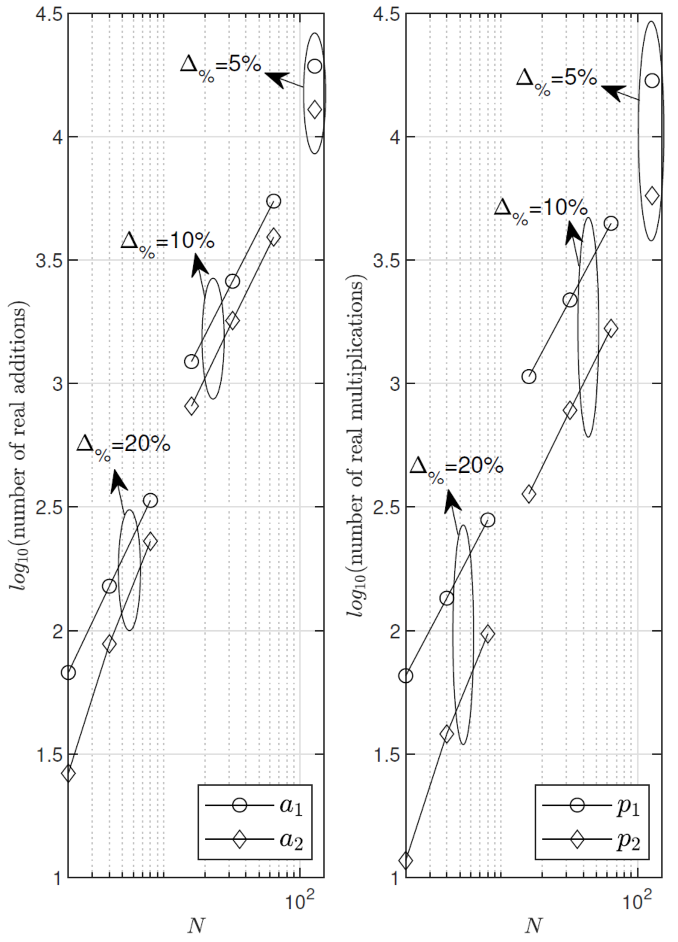
6: $f_a = \frac{f_s}{N} - f_p$

- It is important to note that the frequency-stacked mobile sub-bands do not have uniform spacing across the available Nyquist zone, unlike the evenly spaced DFT modulated filters.
- The prototype filter shall be specified considering the deviation of the subbands from the centre of the DFT modulated filters for each mobile sub-band.



(b)

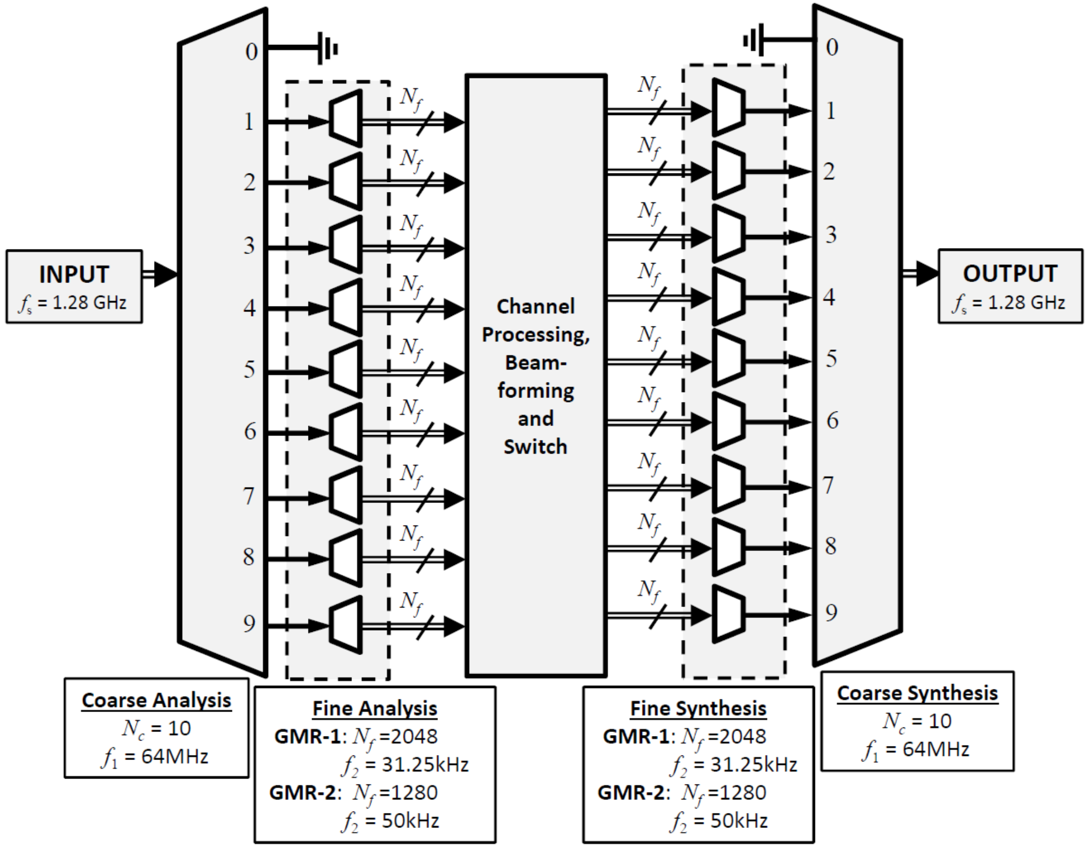
Prototype Filter Specifications



- Two prototype filter candidates were identified
  - Linear Phase FIR
  - Almost Linear Phase IIR
- The computational complexity of the two candidates were formulated and compared for different channel sizes including the FFT operations
- the IIR filter candidate outperforms the FIR filter candidate providing a lower complexity alternative with a lower number of real multiplications and additions in all cases realised.

A. Coskun, S. Cetinsel, I. Kale, R. Hughes, P. Angeletti, and C. Ernst, "Digital Prototype Filter Alternatives for Processing Frequency-Stacked Mobile Sub-Bands Deploying a Single ADC for Beamforming Satellites", IEEE Transactions on Aerospace and Electronic Systems, 2023.

Performance Evaluation



- The high-level model of the OBP developed during the REFLECS project, to test the end-to-end performance of a channeliser, is shown here. The channeliser is based on a two-stage approach, where the Coarse Analysis and Coarse Synthesis form the “coarse channeliser” and similarly the Fine Analysis and the Fine Synthesis form the “fine channeliser”. Channel processing involves all of the baseband processing operations, digital beamforming and switching.
- For our implementation, we examine a total of 9 mobile sub-bands, each received by a distinct antenna element. These sub-bands are then combined in the frequency domain through frequency stacking.

Performance Evaluation

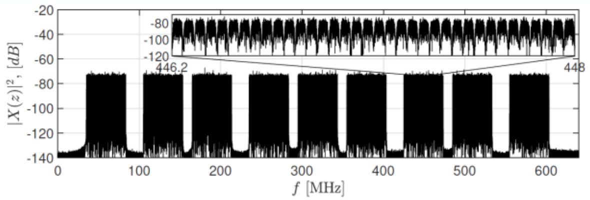
TABLE I
PROTOTYPE FILTER SPECIFICATIONS AND IMPLEMENTATION PARAMETERS

	System Parameters	
Number of Sub-bands (N_c)	10	
DFT Length ($N = 2N_c$)	20	
Sampling Clock Frequency (f_s)	1280 MHz	
Operating Frequency	64 MHz (f_s/20)	
MSS Spectrum	1626.5-1675 MHz Europe (Region 1) L-Band	
Sub-band Centre Frequencies (F_n) at the 1^{st} Nyquist Zone	59.25, 129.25, 189.25, 259.25, 319.25, 379.25, 449.25, 509.25, 579.25 MHz	
Centre Frequencies of the DFT Modulated Filter Bank ($n\frac{f_s}{N}$)	64, 128, 192, 256, 320, 384, 448, 512, 576 MHz	
Centre Frequency Deviation ($\varphi_n = \lvert F_n - n\frac{f_s}{N}\rvert$)	4.75, 1.25, 2.75, 3.25, 0.75, 4.75, 1.25, 2.75, 3.25 MHz	
	Candidate 1	**Candidate 2**
Passband Edge	29 MHz	
Stopband Edge	35 MHz	
Passband Ripple	0.0492 dB	0.00014 dB
Stopband Attenuation	51.42 dB	49.09 dB
Number of filter coefficients	L_{FIR} =600	L_{IIR} =180
Phase deviation	Linear Phase	$< 1^o$
End-to-End MSE Performance (Analysis + Synthesis)	1.29×10^{-6}	1.35×10^{-6}
Power Consumption (Analysis + Synthesis)	4.06 W	3.13 W

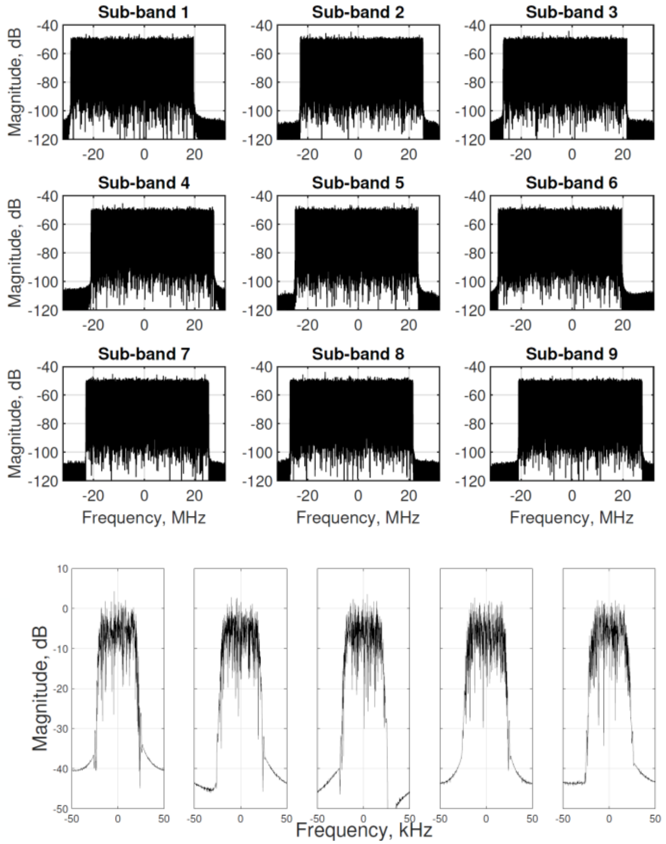
- In order to define the mobile sub-bands, the Europe (Region 1) L-Band MSS uplink spectrum from 1626.5 to 1675 MHz (including the extension band) has been taken into consideration.
- As a result, each mobile sub-band occupies a uniform bandwidth of B = 48.5 MHz, with a centre frequency of fc = 1650.75 MHz. The MSS frequency plans conform to either the GMR-1 or GMR-2 standards. These standards rely on a grid of RF frequencies, differing in both the bandwidth (e.g., 31.25 kHz granularity for GMR-1 or 50 kHz for GMR-2) and the edge frequencies they define.

Performance Evaluation

- The proposed Coarse Analysis enabled the analysis and extraction of the nine frequency-stacked sub-bands. Subsequently, these extracted sub-bands undergo a secondary analysis operation to obtain finer user channels, forming part of the Fine Analysis.
- To achieve this, nine Fine Analysis units are required, one for each sub-band, in order to divide each sub-band into 31.25 kHz granularity for the GMR-1 standard or 50 kHz granularity for the GMR-2 standard.
- An example of successfully retrieved 50 kHz user channels through the Fine Analysis process is shown here for GMR-2.



(a)



Conclusions

- A two stage approach is presented to process frequency-stacked mobile sub-bands.
- We focused mainly on the first stage of this scheme where the Analysis of the frequency-stacked sub-bands is performed using a maximally decimated DFT modulated filter bank
- A practical approach is proposed for processing frequency-stacked mobile sub-bands and the specification of its digital prototype filter.
- Two lowpass prototype filter candidates were considered and compared. The proposed approach implemented and tested in a realistic narrowband communication scenario and the results from this implementation were shared.
- Using an ALP IIR based DFT modulated filter bank saves in the region of 50% power in the Coarse Channeliser and 23% in the overall end-to-end channeliser compared to the Linear-Phase FIR filter based design counterpart.
- It is worth noting that the findings and equations presented here can be easily scaled to accommodate any other wideband ADC or technology.

Thank you for your attention!