Software Defined Radio (SDR) Project

Ahmed Othman
202001131
Communication and Information Engineer
s-ahmed.othman@zewailcity.edu.eg

Yahya Ashraf Mohamed
202000776
Communication and Information Engineer
s-yahya.mohamed@zewailcity.edu.eg

Muhammad Essam
202001411
Communication and Information Engineer
s-mo.essam@zewailcity.edu.eg

Mahmoud Elbahnasawi
202000985
Communication and Information Engineer
s-mahmoud.elbahnasawi@zewailcity

Mario Youchia
201902086
Communication and Information Engineer
s-mario.youchia@zewailcity.edu.eg

Abstract- **This paper presents a comprehensive design and implementation framework for a Narrowband Internet of Things (NB-IoT) base station software-defined radio (SDR) receiver. The project focuses on the development of a finite impulse response (FIR) digital filter to process NB-IoT uplink complex baseband waveforms. The system simulation assumes six NB-IoT devices transmitting their uplink signals in Standalone mode, where the NB-IoT carrier operates outside the LTE spectrum.**

The outline of the paper includes block diagram of the communication system, compliant NB-IoT waveforms, and design of a digital FIR filter using MATLAB. Key aspects include spectral analysis of the baseband signal, determining suitable intermediate frequencies, and iteratively refining the FIR filter design to meet specified criteria. The paper concludes with a discussion on the societal, environmental, and economic implications of NB-IoT applications, particularly in the context of smart healthcare. The proposed project aims to advance NB-IoT base station SDR technology with practical applications in IoT-enabled healthcare.

Keywords- NB-IoT; Software-Defined Radio; Digital FIR Filter; Uplink Communication; Smart Healthcare; IoT Applications;

I. INTRODUCTION

This paper explores the revolutionary impact of Narrowband IoT (NB-IoT) on wireless communication technologies within the Internet of Things (IoT) framework. The focus is on the design and implementation of a Software-Defined Radio (SDR) project for NB-IoT Base Stations, with a specific emphasis on developing a Finite Impulse Response (FIR) digital filter for processing complex baseband waveforms in NB-IoT uplinks. The project simulates the transmission of uplink signals from six NB-IoT devices, demonstrating the versatility of NB-IoT in various communication scenarios.

Key tasks include providing a comprehensive system overview, adhering to NB-IoT standards in waveform generation, and developing a digital FIR filter for signal processing at the base station receiver. This paper explores the specifics of digital filtering and signal processing in an SDR architecture. It presents a block diagram of the communication system in the up-link and describes the NB-IoT waveform simulation using MATLAB. We investigate the spectral properties of NB-IoT signals, demonstrating the need for filtering and the effects this has on the digital signal processing pipeline of the base station.

The research goes beyond technical details to examine the broader effects of NB-IoT applications, especially in smart healthcare. Public health, safety, and social, environmental, and economic aspects related to NB-IoT deployment in healthcare scenarios are all covered in the discussion. With a particular focus on significant applications in smart healthcare, the paper develops NB-IoT technology and its role in reshaping communication systems by merging theoretical insights, simulation results, and a thorough examination of societal implications.

II. PROBLEM STATEMENT

The Main challenge in filter design for a Narrowband Internet of Things (NB-IoT) software-defined radio (SDR) base station receiver is to achieve an ideal balance of multiple filter features. While the ideal filter has a rapid transition between the pass and stop bands, its impracticality due to an infinitely long impulse response necessitates a compromise.

The trade –off between the filter design specifications is mainly between the filter complexity, represented in the filter order, against the favorable constraints we will seek to meet in our design which are: reducing the pass band attenuation, transition region, alongside with increasing the stop band attenuation as much as possible.

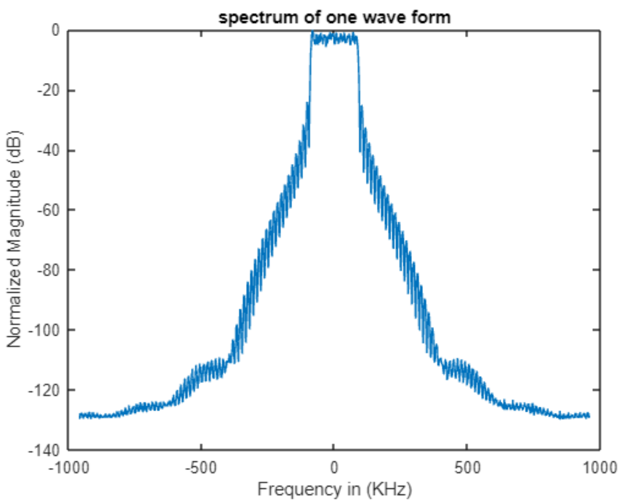
Our primary goal is to effectively reconstruct each of the 6 uplinked signals while keeping in mind the small frequency spread of 15 kHz between signal endpoints.

To accurately reconstruct encoded information bits, the emphasis is on minimizing the "transition region" and securing extremely small pass band ripples. Simultaneously, it is critical to keep the filter order (in other words, the number of filter coefficients) relatively small in order to reduce computational load and overall complexity. This complex design process entails carefully navigating these trade-offs in order to achieve an optimized filter solution for the NB-IoT base station receiver, aligning with specific requirements and constraints.

III. Design Constraints

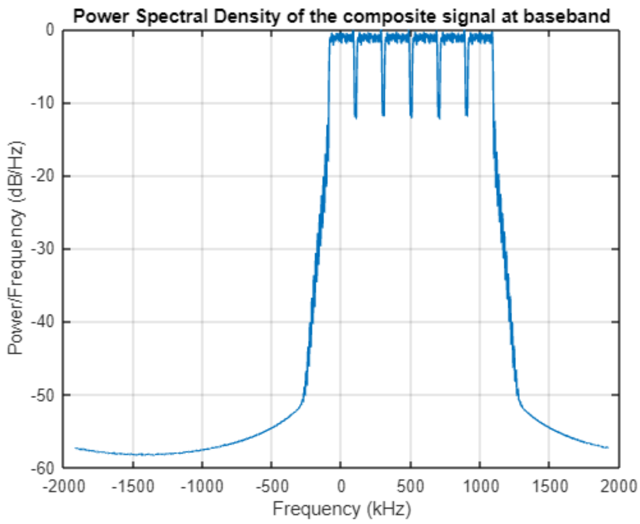
A. The stop band attenuation:

Stop band attenuation is an important aspect of our design considerations. An observation was made by carefully evaluating the magnitude difference within one of the generated signals. The difference between the signal magnitude at "90kHz" (representing the end of the signal's frequency span) and the signal magnitude at "110kHz" (indicating the anticipated initiation frequency of the subsequent signal) is approximately < -25 dB. As a result, the specified constraint for stop band attenuation requires values Less than or equal to 25 dB in the negative domain. This thorough evaluation ensures that our design meets high standards, ensuring optimal performance within the specified stop band attenuation parameters.



B. The transition region:

A critical observation was made while analyzing the transmitted signal, specifically the frequency multiplexing of the six uplink generated signals. Each signal has a bandwidth of "180" kHz, according to the standards outlined in format 1 transmission. The overall frequency span between the center frequencies of every two consecutive signals is set at "200 kHz," with a minimum safeguard band of "30 kHz" between these adjacent signals. As a result, the transition region in our design must span between 25 kHz and a maximum of 30 kHz. This planned separation is critical to ensuring that the attenuation value remains notably small at a distance of <30 kHz from the signal, minimizing any potential signal distortion.



C. Filter Complexity (Filter order):

The filter complexity is represented in the form of a dimensionless number counting the number of coefficients of the filter or the number of taps. The number of coefficients is proportional to the number of multiplications executed through applying the filter. As a result, increasing the number of filters increases the total complexity and computing burden of the filter. Therefore, it will be preferable to decrease the filter order.

Maintaining a filter order below 200 is an ideal goal in the context of the current digital filtering problem. The NB-IoT base station SDR system architecture is complicated, and this strategic limitation ensures a suitable balance between computational efficiency and the filtering needs.

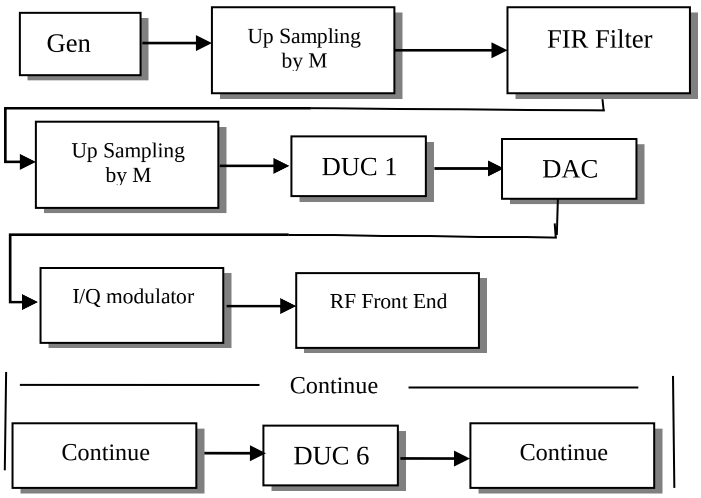
D. Pass band Ripples:

The pass band ripples are important because they reflect the distortion that the filter introduces into the pass band and show how much attenuation is expected in the pass band of the signal. In the current digital filtering challenge ensuring low distortion to our pass frequencies is crucial for the successful reconstruction of the input binary bits created at the transmitter side.

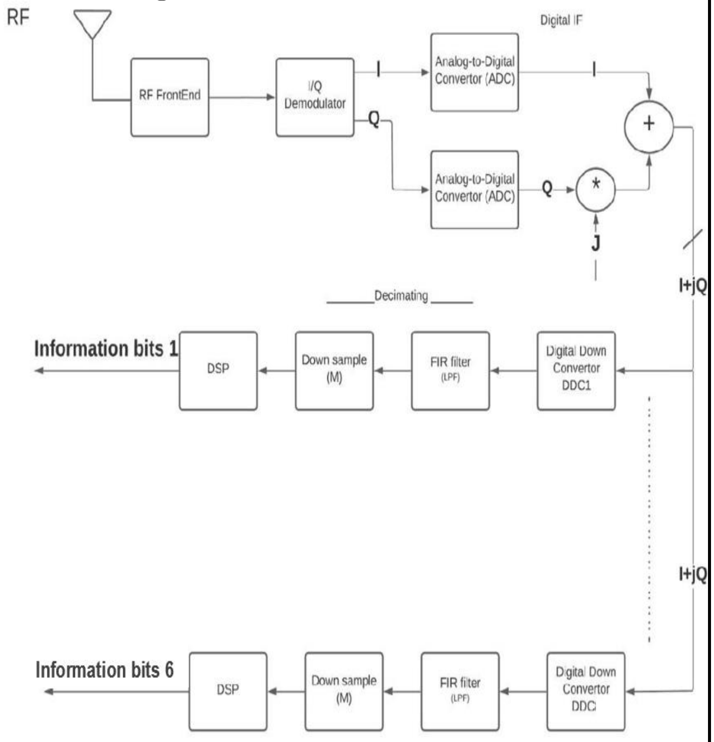
Maintaining low values for pass band ripples is highly critical given the nature of the digital filtering problem. Achieving the least amount of distortion will make it easier to accurately reconstruct the binary information that was delivered. Therefore, it is preferable to target a pass band ripples value <0.2 dB, underscoring the commitment to achieving optimal filtering performance within the NB-IoT base station SDR system.

IV. Block Diagram

Block Diagram of the 8 IoT devices transmitters:



Block Diagram of the base station receiver:



V. Design Process

A. The filter prototypes:

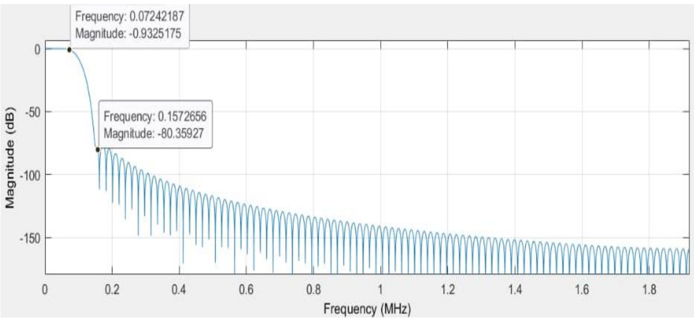
We have chosen 5 different designs in order to iterate and compare every one of the prototypes with the constraints and the requirements we have decided on for our optimal filter design. The following table shows the five designs input arguments given for every one of the five design methods.

	Black Man	Least-Squares	Chebyshev	Equiripple
Order	200	200	200	Min
Fs	3840000	3840000	3840000	3840000
Fc	95000	-	95000	-
Side-lobe Atten	-	-	100	-
Fpass	-	90000	-	90000
Fstop	-	110000	-	110000
Apass	-	-	-	1
Astop	-	-	-	40
Density Factor	-	-	-	20
Wpass	-	1	-	-
Wstop	-	1	-	-

B. Qualitative analysis of the prototypes

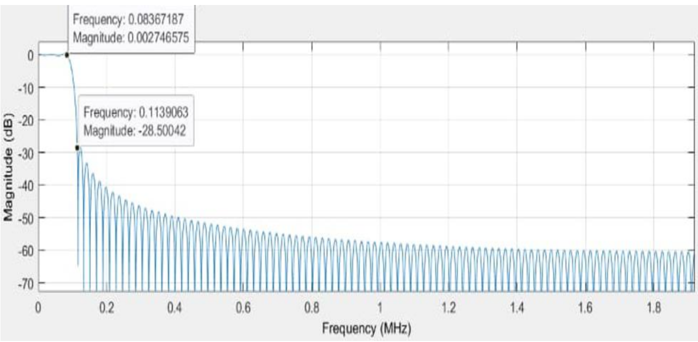
1) Blackman (Window):

Despite achieving commendable results concerning pass band ripples and stop band attenuation, the Blackman window filter faced challenges in maintaining an acceptable transition region bandwidth. Furthermore, the complexity of the filter was found to be relatively high. This observation underscores the need for a more refined balance between performance metrics and computational efficiency in order to meet the project's specifications.



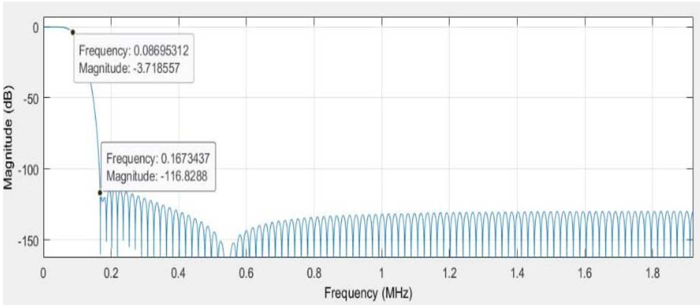
2) Least-Squares:

This filter prototype performed well at lower orders, maintaining an acceptable range of values for pass band ripples. However, problems arise due to the filter's stop band attenuation, which is significantly distorting and has the potential to cause damage to our signal integrity. Furthermore, when the frequency response of the filter is visualized on a linear scale, it is clear that the transition region bandwidth is insufficient for our intended filtering process. Despite these considerations, the filter remains an attractive option that requires further evaluation and refinement to address the identified limitations.



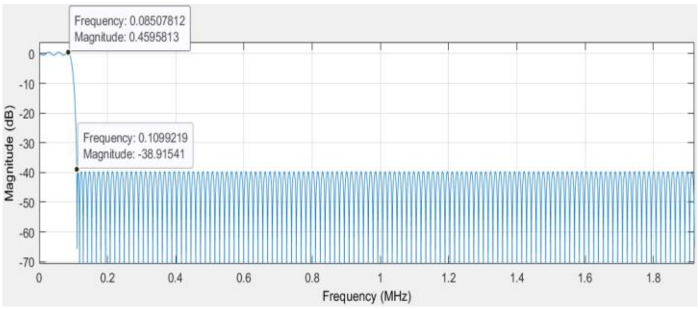
3) Chebyshev (Window):

This filter prototype performed well but still did not achieve our target.



4) Equiripple:

The Equiripple filter has accomplished a commendable compromise among the specified filter constraints. Notably, it exhibits satisfactory stop band attenuation and transition region bandwidth, as well as pass band ripples with relatively favorable values. Given these performance characteristics, this filter requires careful consideration in the ongoing evaluation process.

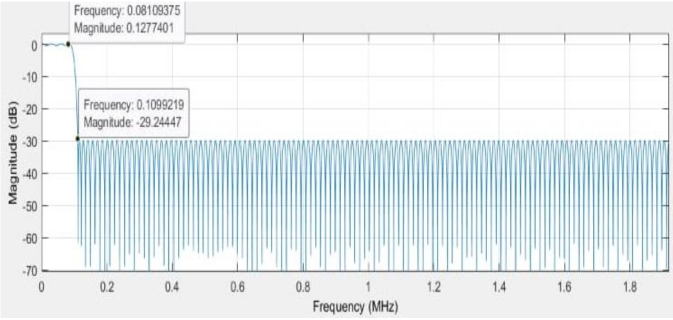


C. Quantitative Analysis

The next step includes calculating the values of the filter parameters represented in: Filter order, Pass band ripples, Stop band attenuation, and transition region bandwidth. The following table illustrates the output values of each of the five prototypes.

Filter-Design	Black Man	Least-Squares	Chebyshev	Equiripple
Scors	8	8	7	7
Order	199	200	200	273
Pass-Band Ripples (dB)	0.02	0.201	0.02	1
Stop-Band Attenuation (dB)	-79.4	-29.497	-112.3	-112.3
Transition Bandwidth (kHz)	87 kHz	30.23 kHz	87 kHz	24.8 kHz

After iterations Equiripple achieved a Score: 9 with Order: 258, passband Ripple: 0.215, stopband Attenuations: -29.073, transition BW: 28.9 kHz



D. Evaluation Criteria

The selection will be based upon the constraints and requirements we have stated. Each prototype will be given a score of compatibility to measure the convenience of each design. The score will be given out of 8 points;

2 for each constraint. Every prototype will be given a number of points for each constraint ranging from "0" to "3" according to the level of resemblance compared to our designed constraint. The design that will achieve the highest score of compatibility with our design constraints will be utilized in both the transmission and the reception processes. The following table shows the scoring range for each filter parameter.

Score	0	1	2	3
Order	> 300	200:300	100:200	<100
Passband ripples [dB]	> 0.4	0.3:0.4	0.2:0.3	<0.2
Stopband attenuation [dB]	<-60	-25:-60	-15:-25	>-15
Transition bandwidth [kHz]	>80	50:80	30:50	<30

VI. IMPLEMENTATION

1) Evaluation Criteria

Scoring every design will be done using an iterative code which will give a certain score for each prototype based on the above criteria and choose the most convenient design according to our digital filtering problem.

Constructing an array holding the specifications of the five proposed prototypes. The specifications are: pass band ripples(dB), stop band attenuation(dB), transition region band width (kHz), and filter order, respectively. The filter design process will include an iteration process on the specifications of the five designs and scoring each design based on the quantitative evaluation criteria attached. The prototype having the highest score will be implemented within the transmission and receiving stages.

```
clc;
```

```
optimalfil-
ter=cell2mat(struct2cell(load('3_Equiripple.mat')));
```

```
optimalfil-
ter=cell2mat(struct2cell(load('3_Equiripple.mat')));
numDevices = 6;
IF_frequency_spacing = 200e3 ;  % Frequency spacing be-
tween NB-IoT carriers in Hz
IF_center_frequency = 0;  % Start at 0 Hz  % Center fre-
quency for the composite IF signal in Hz
IF_carrier_freqs = IF_center_frequency + (0:numDevices-1)
* IF_frequency_spacing;
% Display the calculated IF frequencies
disp('Calculated IF Frequencies for 6 NB-IoT Devices:')
disp(IF_carrier_freqs)
% Cell array to store waveform and sampling rate for each
device
waveforms = cell(1, numDevices);
samplingRates = cell(1, numDevices);
```

Intializing the filter coefficients:

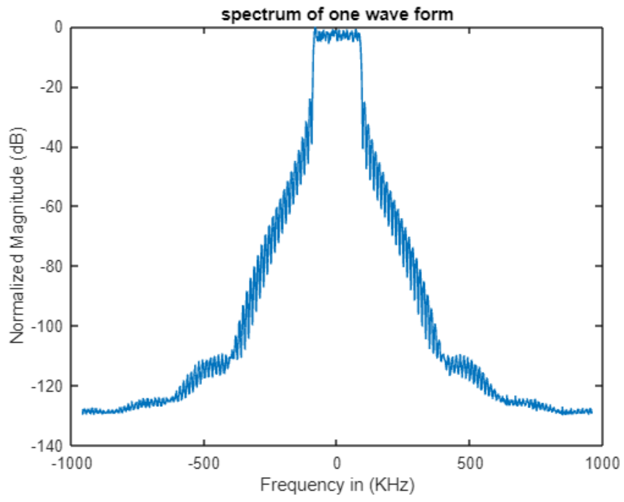
Generating the 6 waveforms:

```
% Loop through each device and generate waveform
for deviceIdx = 1:numDevices
    % Call the generate_NBiot_UL function
    [waveform, Fs] = Generate_NBiot();
    % Store waveform and sampling rate in cell arrays
    waveforms{deviceIdx} = waveform;
    samplingRates{deviceIdx} = Fs;
end
```

Display information about the generated waveform for one of the devices:

```
% Display information about the generated waveform for
each device
disp(['Generated NB-IoT Uplink Waveform Information for
Device ' num2str(deviceIdx) ':']);
disp(['Sampling Rate (Fs): ' num2str(Fs) ' Hz']);
disp(['Waveform Length: ' num2str(length(waveform)) ' sam-
ples']);
[signal,f] =
pwelch(waveform,2048,1024,2048,Fs,"centered");
signal = signal/max(abs(signal));
plot(f/1e3,20*log10((signal)))
xlabel('Frequency in (KHz)')
```

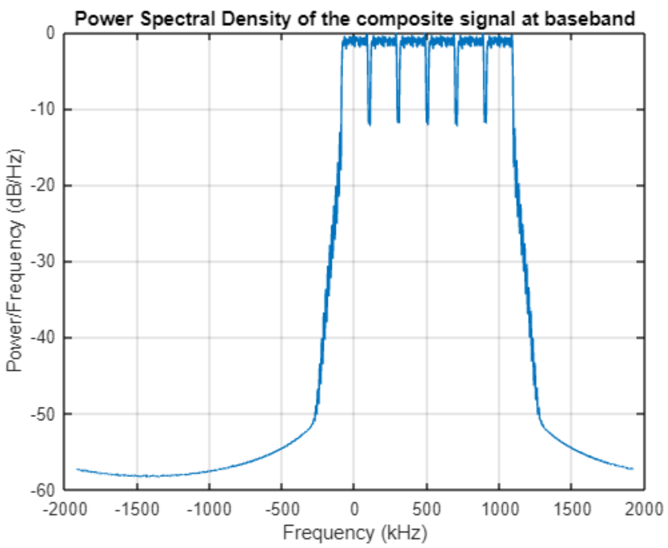
```
ylabel('Normalized Magnitude (dB)')
title ('spectrum of one wave form')
```



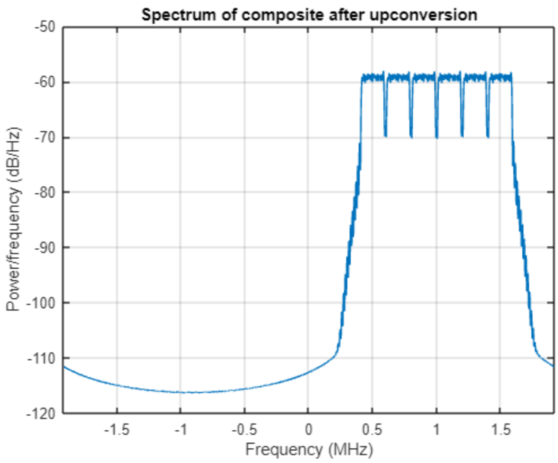
Creating the composite IF signal:

```
% Create the composite IF signal
composite_IF_signal_upsampled = ze-
ros(1,2*length(waveforms{1}));  % Initialize with the size
of one waveform
IF_sampling_rate = 2 * max(IF_center_frequency + (numDevices
- 1) * IF_frequency_spacing, Fs);
upsampling_factor = IF_sampling_rate/Fs;
upsampled_signal=zeros(1,2*length(waveforms{1}));
for i = 1:numDevices
        upsampled_signal = upsample((waveforms{i})', upsam-
pling_factor);
         % Apply low-pass filter
%          lpf = lowpass('Fp,Fst,Ap,Ast', cutoff_frequency,
cutoff_frequency * 1.5, 0.1, 80, Fs * upsampling_factor);
        cutoff_frequency = IF_frequency_spacing / (2 * up-
sampling_factor);


        filtered_signal= low-
pass(upsampled_signal,cutoff_frequency,IF_sampling_rate);
%          filtered_signal = filter(lpf, 1, upsam-
pled_signal);

        % Calculate the carrier frequency for the current
device
%          carrier_frequency = IF_center_frequency + (de-
viceIndex - 1) * IF_frequency_spacing;

        % Perform digital upconversion by multiplying with a
complex exponential
        t = (0:length(filtered_signal)-1)/ Fs / upsam-
pling_factor  ;
        upconverted_signal = filtered_signal .* exp(1i*2 *
pi * IF_carrier_freqs(i) * t);
```

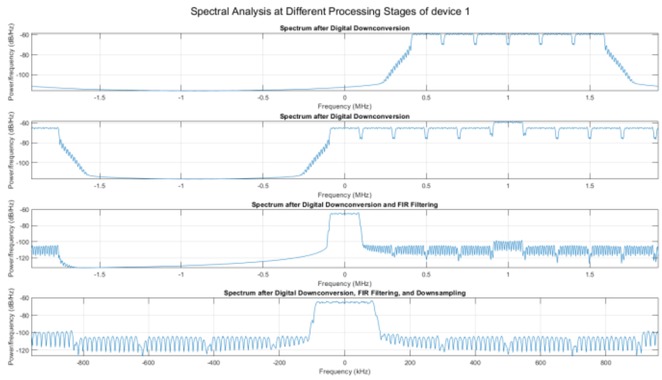
```
        % Add the upconverted signal to the composite IF
signal
        composite_IF_signal_upsampled = compo-
site_IF_signal_upsampled + upconverted_signal;
end
% Plot the magnitude spectrum of the composite IF signal
[IF_signal_spectrum, IF_frequencies] =
pwelch(composite_IF_signal_upsampled, 2048, 1024, 2048, Fs
* upsampling_factor,"centered");
IF_signal_spectrum = IF_signal_spectrum /
max(abs(IF_signal_spectrum));
% Plot the magnitude spectrum
figure;
plot(IF_frequencies/1e3, 10*log10((IF_signal_spectrum)));
% Using log scale for better visualization
xlabel('Frequency (kHz)')
ylabel('Power/Frequency (dB/Hz)')
title('Power Spectral Density of the composite signal at
baseband')
grid on;
```

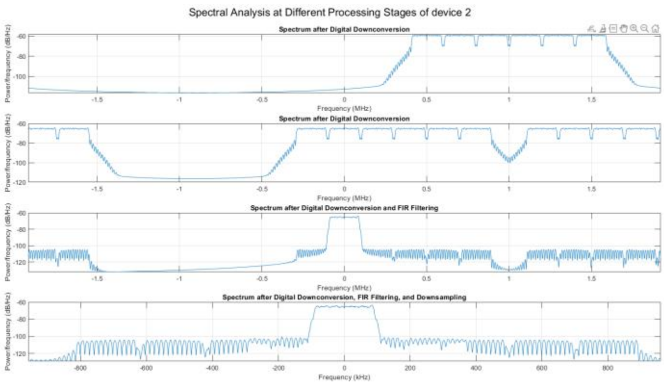


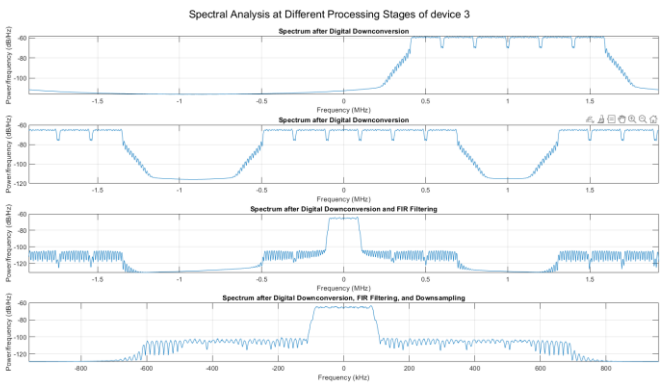

```
IF_freq = 500e3;
compo-
site_IF_signal_upsampled=composite_IF_signal_upsampled.*ex
p(1i*2 * pi * IF_freq * t);
pwelch(composite_IF_signal_upsampled, 2048, 1024, 2048,
IF_sampling_rate, 'centered');
title('Spectrum of composite after upconversion');
```

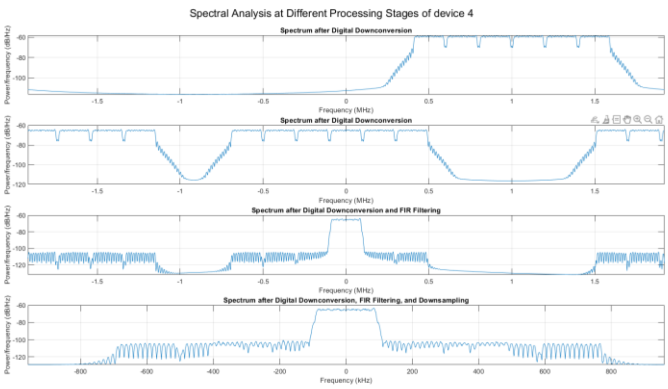


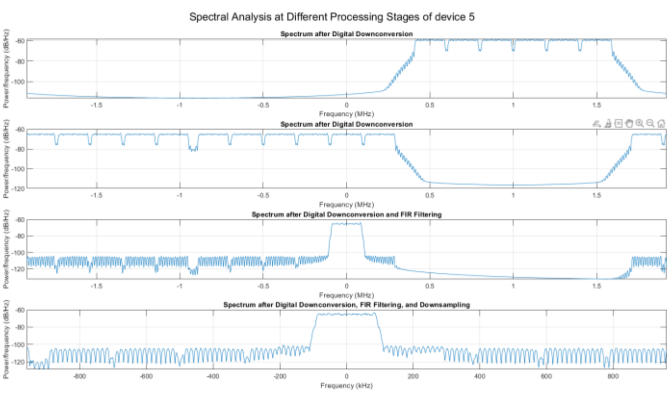

```
%receiver
received_waveforms_down_converged = ze-
ros(6,length(composite_IF_signal_upsampled));
received_downsampled = zeros(6,length(waveform'));
receivedfil-
tered_signal=zeros(6,length(composite_IF_signal_upsampled'))
;
rx_signal_spectrum= zeros(6,length(signal));
f2=zeros(6,2048);
for i=1:6
    re-
ceived_waveforms_down_converged(i,:)=composite_IF_signal_ups
ampled.* cos(2 * pi *(IF_freq + IF_carrier_freqs(i)) * t);
    receivedfiltered_signal(i,:) = fil-
ter(optimalfilter,1,received_waveforms_down_converged(i,:));
    downsampling_factor = upsampling_factor;
    received_downsampled(i,:) = downsam-
ple(receivedfiltered_signal(i,:), downsampling_factor);

end
for n =1 : 6
figure;
subplot(4,1, 1);
pwelch(composite_IF_signal_upsampled, 2048, 1024, 2048,
IF_sampling_rate, 'centered');
title('Spectrum after Digital Downconversion');
subplot(4,1, 2);
pwelch(received_waveforms_down_converged(n,:), 2048, 1024,
2048, IF_sampling_rate, 'centered');
title('Spectrum after Digital Downconversion');
subplot(4, 1, 3);
pwelch(receivedfiltered_signal(n,:), 2048, 1024, 2048,
IF_sampling_rate, 'centered');
title('Spectrum after Digital Downconversion and FIR Filter-
ing');
subplot(4, 1, 4);
pwelch(received_downsampled(n,:), 2048, 1024, 2048,
IF_sampling_rate/downsampling_factor, 'centered');
title('Spectrum after Digital Downconversion, FIR Filtering,
and Downsampling');


sgtitle(['Spectral Analysis at Different Processing Stages
of device ',int2str(n)]);
```

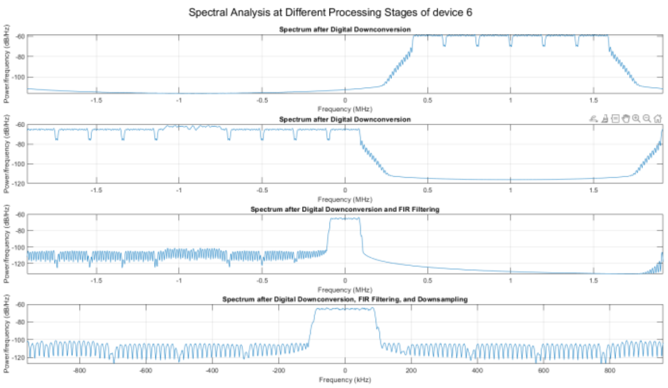












VII. NB-IoT APPLICATION

One notable application of Narrowband Internet of Things (NB-IoT) technology with significant implications for public health, safety, and various societal aspects is in the domain of smart cities, specifically in the implementation of smart healthcare solutions.

The integration of NB-IoT in healthcare applications brings about a range of benefits, but it also raises considerations related to public health, safety, environment, and economic factors.

Smart Healthcare Application of NB-IoT *(In-Depth Exploration):*

1. **Public Health and Safety:**

- **Remote Patient Monitoring:** NB-IoT enables the continuous monitoring of patient's vital signs and health parameters remotely. This application is particularly valuable for patients with chronic illnesses or those in remote locations, ensuring timely medical interventions and reducing the need for frequent hospital visits.

- **Early Disease Detection:** NB-IoT facilitates continuous health monitoring, enabling early detection of anomalies or potential health risks. This proactive approach aids in the early diagnosis and management of diseases, contributing to public health initiatives.

- **Emergency Response Systems:** The use of NB-IoT facilitates the development of advanced emergency response systems. Wearable devices equipped with NB-IoT connectivity can transmit real-time health data to emergency services, enabling faster and more accurate responses during critical situations.

- **Epidemic Surveillance:** In the context of pandemics or disease outbreaks, NB-IoT-based systems can be deployed for real-time monitoring of symptoms, contact tracing, and ensuring adherence to preventive measures, thus enhancing public safety.

2. **Social Factors:**

- **Improved Access to Healthcare:** NB-IoT contributes to democratizing healthcare by enhancing access to medical services. Remote monitoring and telemedicine applications can bridge geographical gaps, providing healthcare services to individuals in underserved or remote areas.

- **Enhanced Quality of Life:** Smart healthcare solutions leveraging NB-IoT can improve the overall quality of life for individuals with chronic conditions. Continuous monitoring and early detection of health issues contribute to proactive healthcare management.

- **Elderly Care and Independent Living:** NB-IoT-powered wearables and home monitoring devices provide a safety net for the elderly. These devices can detect falls, monitor vital signs, and enable seniors to age in place independently, reducing social isolation and improving overall well-being.

- **Chronic Disease Management:** For individuals managing chronic conditions, NB-IoT facilitates the continuous monitoring of parameters such as blood glucose levels or heart rate. This data can be shared with healthcare providers, fostering personalized care plans and reducing the societal burden of chronic diseases.

3. **Environmental Factors:**

- **Reduced Carbon Footprint:** The implementation of remote patient monitoring and telehealth services through NB-IoT can contribute to a reduction in the carbon footprint associated with travel to healthcare facilities. Fewer physical appointments may translate to decreased emissions from transportation.

- **Efficient Resource Utilization:** NB-IoT enables healthcare providers to allocate resources more efficiently by focusing on individuals who require immediate attention. This optimized resource allocation contributes to a more sustainable healthcare system.

- **Green Healthcare Practices:** NB-IoT contributes to greener healthcare by minimizing the need for physical appointments and hospital visits. Remote monitoring reduces the environmental impact associated with travel, waiting areas, and the production of disposable medical supplies.

- **Energy-Efficient Infrastructure:** NB-IoT devices are designed to be energy-efficient, ensuring minimal impact on the environment. Low power consumption extends the lifespan of devices and reduces the need for frequent battery replacements.

4. **Economic Factors:**

- Cost-Efficiency: By reducing the frequency of hospital visits and preventing complications through early detection, NB-IoT applications in healthcare can lead to cost savings for both individuals and healthcare systems.

- Job Creation: The implementation of NB-IoT in healthcare necessitates the development and maintenance of IoT infrastructure, creating job opportunities in technology, healthcare, and related sectors.

- Preventive Healthcare Cost Savings: Early detection and management of health issues through NB-IoT result in cost savings for both individuals and healthcare systems. By addressing health concerns at an early stage, the financial burden of extensive treatments and hospitalizations is reduced.

- Health Data Analytics: NB-IoT generates a wealth of health data, contributing to health analytics and research. This data-driven approach aids in evidence-based decision-making, optimizing healthcare resources, and fostering economic growth in the health technology sector.

5. **Data Security and Privacy:**

- Secure Health Data Transmission: NB-IoT networks are designed with robust security features to ensure the safe transmission of sensitive health data. Encryption protocols and secure communication channels protect patient privacy and maintain the confidentiality of medical information.

6. **Interconnectivity and Interoperability:**

- Integrated Healthcare Ecosystem: NB-IoT supports the seamless integration of diverse healthcare devices and systems, fostering an interconnected healthcare ecosystem. This interoperability enhances care coordination, streamlining the exchange of information among healthcare providers and improving patient outcomes.

VIII. CONCLUSION

In conclusion, the Software Defined Radio (SDR) project for an NB-IoT base station receiver represents a comprehensive and systematic approach to tackle the challenges of digital filtering in NB-IoT uplink communication. The emphasis on developing a Finite Impulse Response (FIR) digital filter highlights the importance of achieving an optimal balance in filter characteristics. The project includes a clear block diagram overview of the uplink communication system, detailing the transmitters of six NB-IoT devices and the base station receiver. The MATLAB-based simulation, along with the iterative FIR filter design process, demonstrates a methodical approach to meet strict specifications and constraints.

A qualitative analysis of various filter prototypes reveals strengths and limitations, with the Equiripple filter emerging as a promising candidate due to its balanced trade-off among key parameters. The quantitative analysis further assesses each prototype's performance against critical parameters, facilitated by a systematic scoring mechanism for selecting the most compatible filter design.

Going beyond technical aspects, the paper explores broader implications of NB-IoT applications, particularly in smart healthcare, covering public health, safety, societal, environmental, and economic factors. Overall, the project contributes significantly to advancing NB-IoT technology, specifically in the context of smart healthcare, combining theoretical insights, simulation results, and a thorough examination of societal implications.

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