BERZIET UNIVERSITY

FACULTY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

ENEE 4113

communication Laboratory.

Experiment 7

Pulse Code Modulation (PCM)

Prepared by: Anas Nimer 1180180

Instructor: Dr. mohammad jubran

TA: Eng.Ruba Eid

Section #: 3

Date: 10.4.2021

1. Abstract:

In this experiment, the students will be introduced about pulse code modulation, how they can coding any message signal in order to use it in digital world, to apply some analysis, memorize the sound wave, and computation on this message by the huge computation power and memory of the computer, This experiment will iteratively walk with the students to carry out the steps of PCM such as the quantization and encoding steps and will introduce linear (Mid-rise and Mid-tread) , non-linear quantization, quantization of weak signal to grant the student a full understanding regarding this topic. Finally, the student will understand how the quantization of real audio signal works in real life.

Contininent:

Table of figure:

2. <u>Procedure:</u>

2.1 Characteristic of Uniform (Linear) Quantizer with DC input:

In this section we will obtain the input-output characteristic of a linear quantization over a constant number as quantization levels. First of all we will made the quantization over 4 levels, this will be 2 bits, so the linear quantization suggests to make the levels = 2^n , which n is any positive integer, the dynamic range of this quantization is [-10,10] which means that this range will be divided into 4 equal slots, any two or more message values that are in the same slot will out the same quantizer value as shown below, <u>the step size can be calculated as: length of the dynamic range / number of levels</u>.

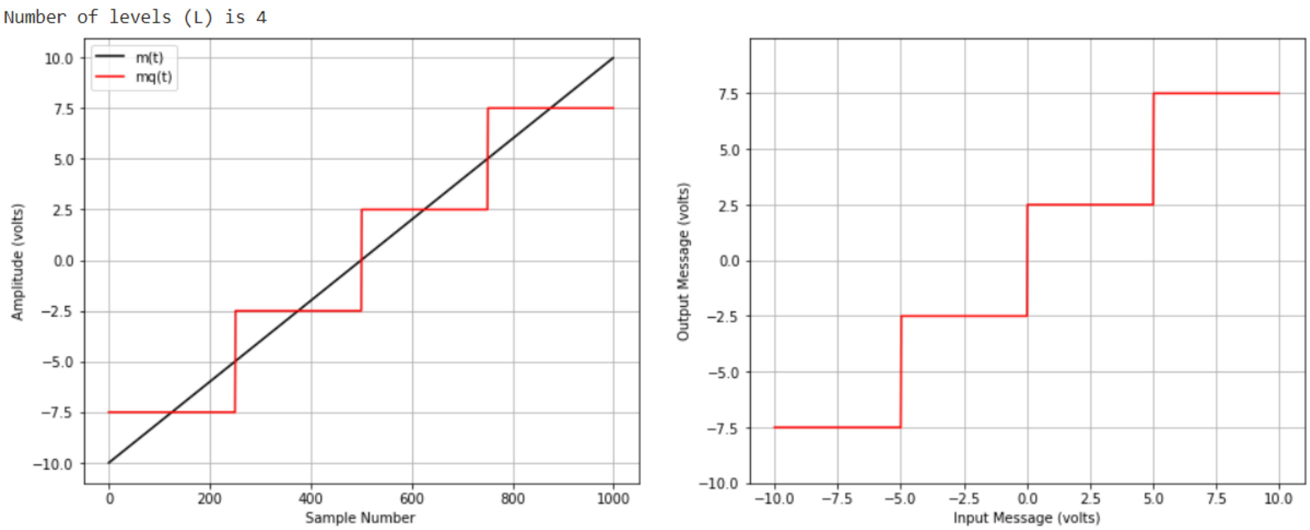

Figure 1:message and quantizer and the output

- **<u>Note</u>**: As shown above, the step size = {(10 - -10)/4} =5, that means any sample value between (-10, -5) will be regarded as -7.5, any value lies on (-5,0) will be regarded as -2.5 and so on, the output result of this process shown in part 2 from above figure.

Exercise:

1- change number of level to 8:

Number of levels (L) is 8

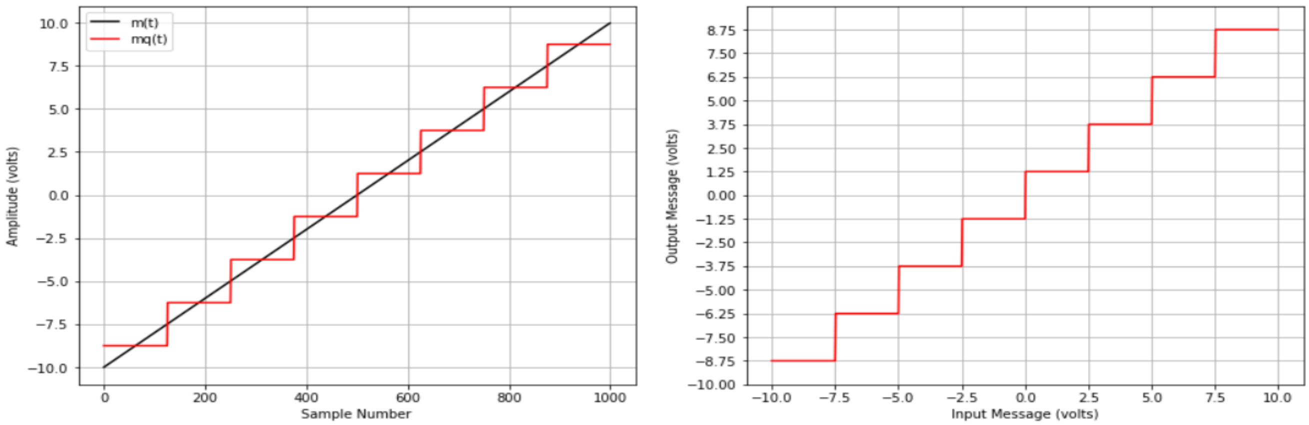

Figure 2:message and quantizer and the output when L=8

- **<u>Note</u>**: We notice from the above figures that we have increased the number of level by increasing the number of bits where L(# of level) = 2^n where n: # of bits => $8=2^3$.
  Also We notice increasing the number of level affects the step size where step size = (dmax-dmain)/ L. So when L increased the step size will be decreased for example, in this case the step size= (10- -10)/8=2.5 and this number remains constant over all the levels. Also the destination will be increased. We also note that any value for massage ranges between (-10, -7.5), for example, which is rounded to -8.75 and that any value for massage ranges between (-7.6, -5), for example, which is rounded to -6.25 and so on.

2- change the number of levels to 16:

Number of levels (L) is 16

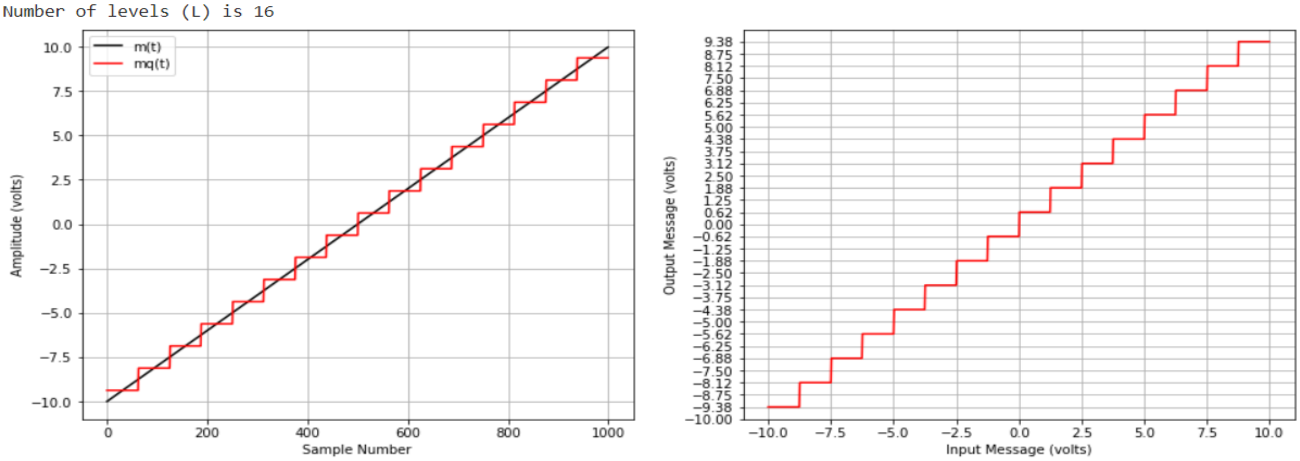

Figure 3:message and quantizer and the output when L=16

- **<u>Note</u>**: in this case we need 4 bits to make the level = 16, and we notice from above figure the step size was decremented base on the number of levels, the output of the quantizer in this case is closer to the message.

2.2 Characteristic of Mid-rise and Mid-tread Uniform (Linear) Quantizers:

In this section, we will understand the difference between Mid-rise and Mid-tread quantization, to show that we will quantize the same message in the two case studies over the same number of levels which is equal to 2^n where n is positive integer that represent the number of bits used to encode the levels, firstly we will set n = 2, and the dynamic range = [-10,10]. The difference between mid-raise and mid-tread is in the setting of their levels, the mid-tread quantizer has a level for the zero output value as shown in Fig4.

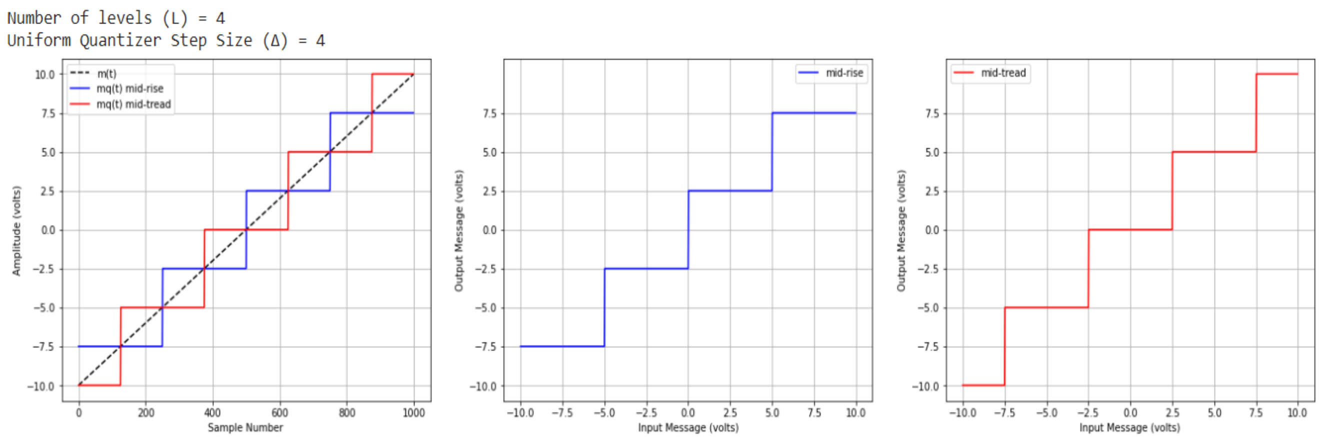

Figure 4:quantization of mid-rise then of mid-tread

- **Note**: As we can see, the mid-rise quantizer creates a symmetric distribution of quantization levels, whereas the mid-tread quantizer has more levels below zero than above zero, but the mid-tread quantizer cannot be symmetric in any case. Also #of level in mid rise = 2^n (# of level even) but #of level in mid tread= 2^n+1 (# of level odd). In addition to, we can notice the mid rise is inverse for mid tread and the step size in the two cases equals.

Exercise:

1- **<u>Let's change the number of bits used to encode the levels to n=4:</u>**

```
Number of levels (L) = 16
Uniform Quantizer Step Size (Δ) = 16
```

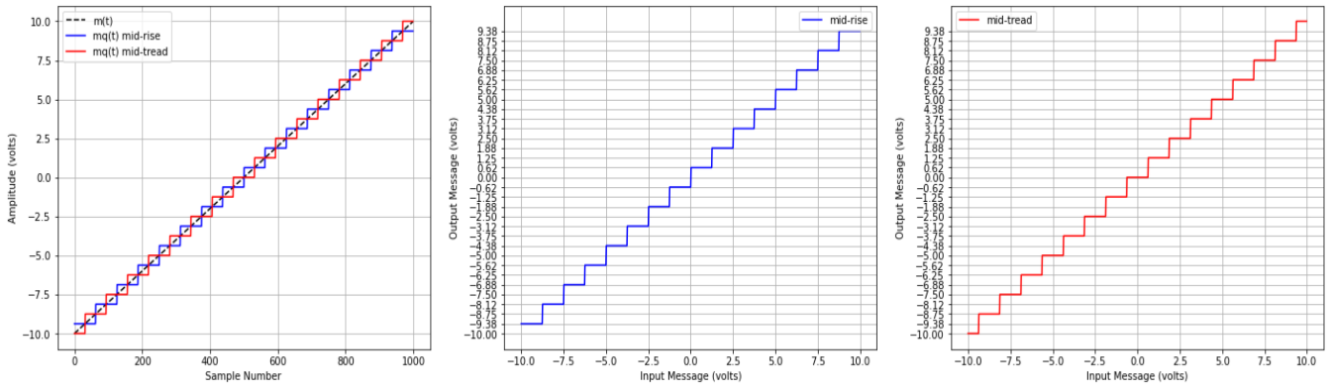

Figure 5:quantization when n=4

- **<u>Note</u>**: we can notice from above figure, when increase the number of bits then the #of level change by $2^n = 16$, and the step size changed to (10- -10)/16= 1.25. so when increased the number of bits, the number of level will increase and the output will be closer to the massage.

2.3 Characteristic of Robust (Non-Linear) Quantizer with DC input:

In this section, we aim to obtain both the characteristic of the compressor at the transmitting side and the expander at the receiving side. Firstly, we build μ-Law compressor and μ-Law expander for $\mu = 255$. Fig6 show the characteristic of compressor and the expander respectively over dynamic range = [-10,10].

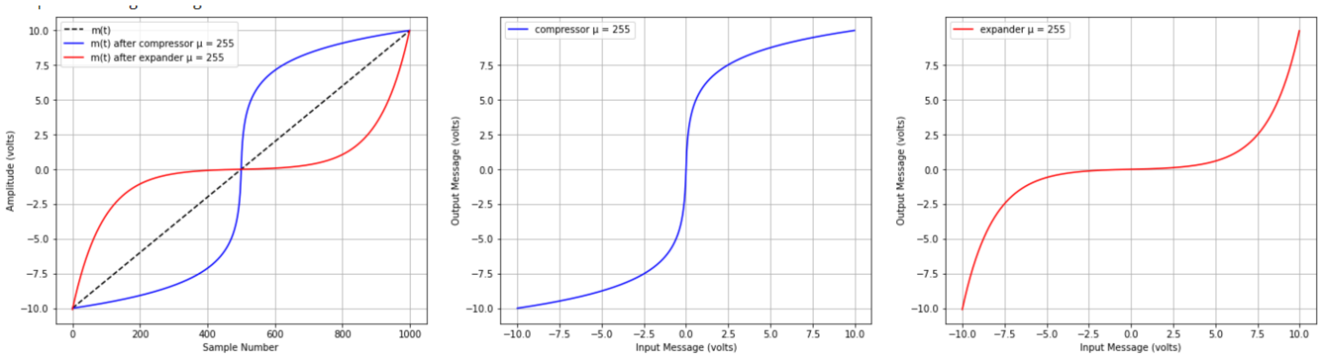

Figure 6: compressor & expander

- **Note**: As seen in part2 of figure above, the characteristic of the compressor is logarithmic in nature. Small amplitudes are greatly amplified while the large amplitudes are barely amplified according to μ-law, for example if we take value from massage input like 2.5 this value greatly amplified to 7.3, but if we take another value from the massage like 8 this value greatly amplified to 9. But in part3, it is evident that the expander is the inverse of the compressor in order to introduce in order no distortion to the system, where small signal amplitudes are multiplied by smaller factors and high amplitudes are multiplied with larger ones, in order to remove the effect of compression and reconstruct the original signal to take back the original message.

Let’s change the value of μ to 5,50,225 and see how it affect the compressor and the expander as shown below.

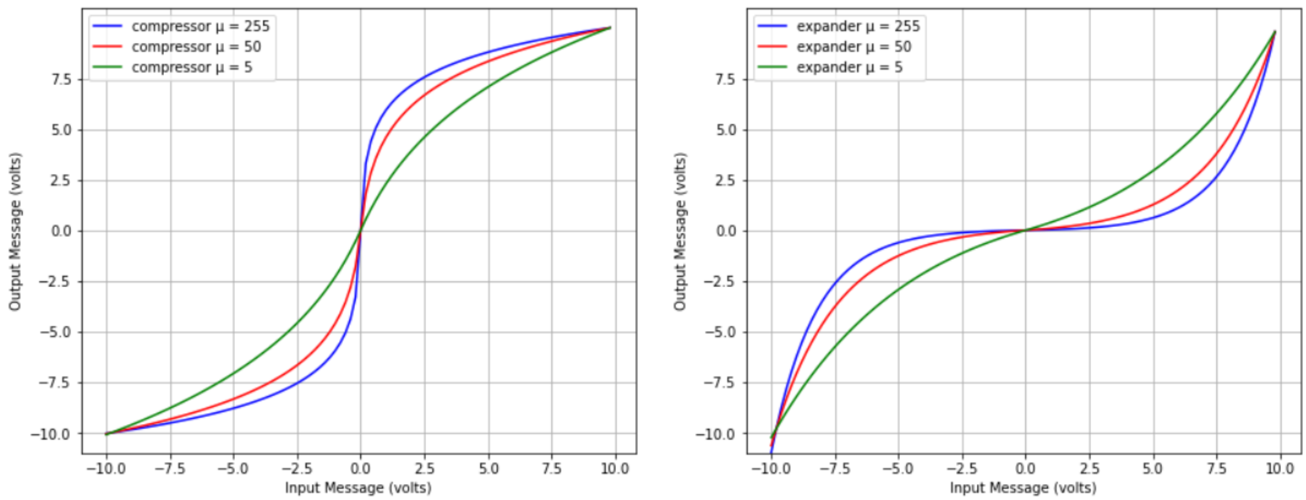

Figure 7:compressor & expander with different μ

- **<u>Note</u>**: We observe from figure above that when we decrease the value of μ the slope will decrease too and the characteristic will go more and more to be closer to linear, in other words, the effect of the compressor and the expander on the modulated values will decrease if the μ decrease and vice versa in case of increasing. As we saw in figure ubove, when we increase the μ value we will get a characteristic closer to the logarithm so we take care of the low frequency more and more and that is what we need, so we will consider μ =225 as our standard value for the rest of this experiment.

Now let's go and try to quantize the same message in linear and robust mode to see the difference between them with n=4, dynamic range =[-10,10], and μ=255 for robust compressor.

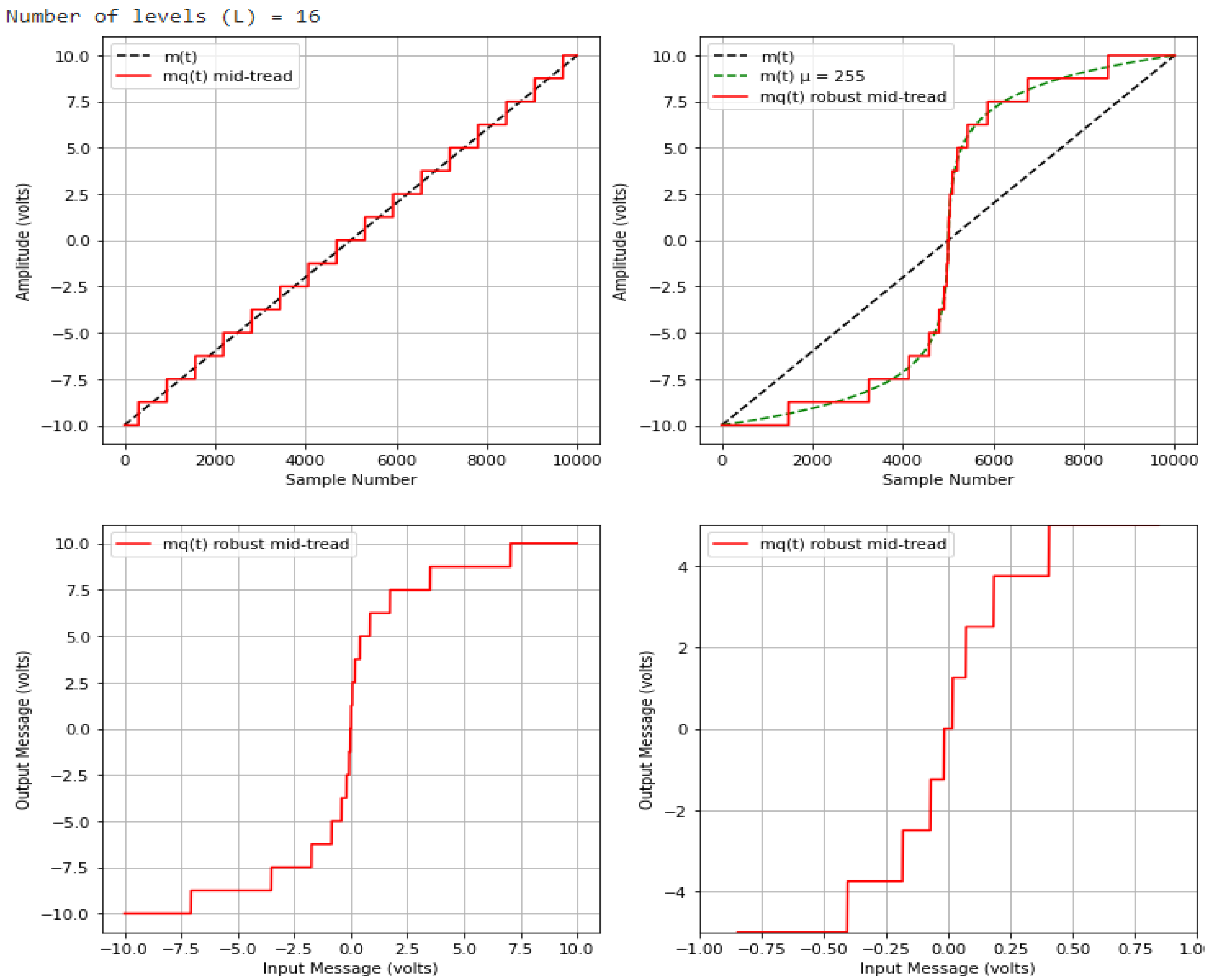

Figure 8:linear quantization & robust quantization

- **Note:** As we see from above figures that the quantization of part 1 from above figure is linear and all the steps size are equal, but in part 2,3,4 the step size follows to logarithm in order to take care of the low frequencies. So in part2 from figure above we notice if we take a value from the massage between (0 and 5), it will be representation to a greater than one level, while if we take a value between (7.5 and 10), a representation occurs on it with only one level. Also If we vary n, the number of steps will vary according to 2^n and the size of each step will be varied as we said in the previous section. If we tend to vary value of μ the characteristic of the quantizer will be varied as we explain above.

2.4 Uniform Quantization of Single Tune Message Signal:

In this part of the experiment, we will take a single tune message (sine or cosine) then sample it at Fs >2W to avoid the aliasing, then we will quantize the sampled signal as we saw above then input this to LPF with cut-off = Fs/2.

Let us try this on cosine signal with Fm=10, Am=1, and Fs=100 which is >2W, and then apply the quantization with n=4, that leads us to have 16 levels of quantization, the dynamic range of this case=[-1,1] this is the range where we see the message and in this case the massage is wrong because the dynamic value is proportional to the amplitude of the massage. All of the process shown below **(first case)**:

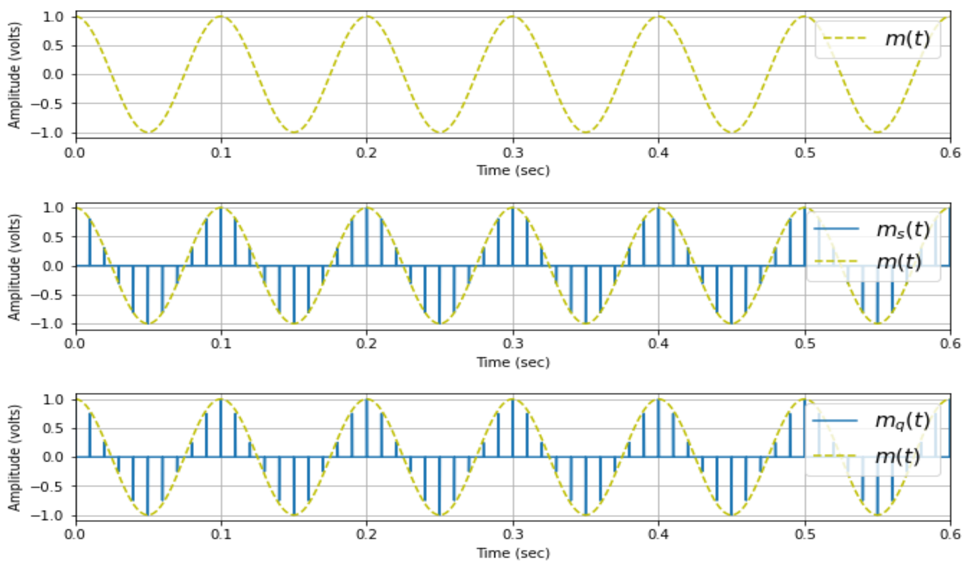

Figure 9: massage signal & sampled signal & output of quantizer in time domain

- **Note**: we can show from above figure, the original message in times domain in first plot from top, then the sampled signal, then the output of the quantizer as quantized signal, we can't observe the difference between the sampled and the quantized signals in this domain because we made the quantization on 16 levels which is enough, later, we will try it with lower number of levels to see the difference. After quantization we enter the quantized signal into LPF with cut-off frequency =Fs/2 to reconstruct the signal as shown below:

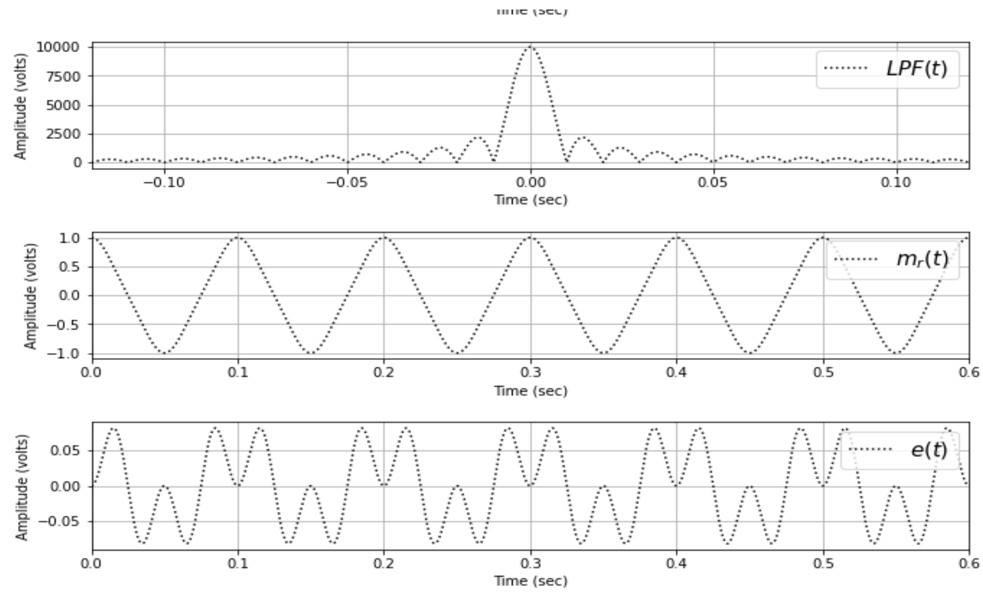

Figure 10: LPF & m^(t) & error signals in time domain

- **<u>Note</u>**: above figure shows the LPF used to reconstruct the signal in time domain in first plot, then the reconstructed signal, then the error between the sampled and reconstructed signal is little, so we can reconstruct the message.

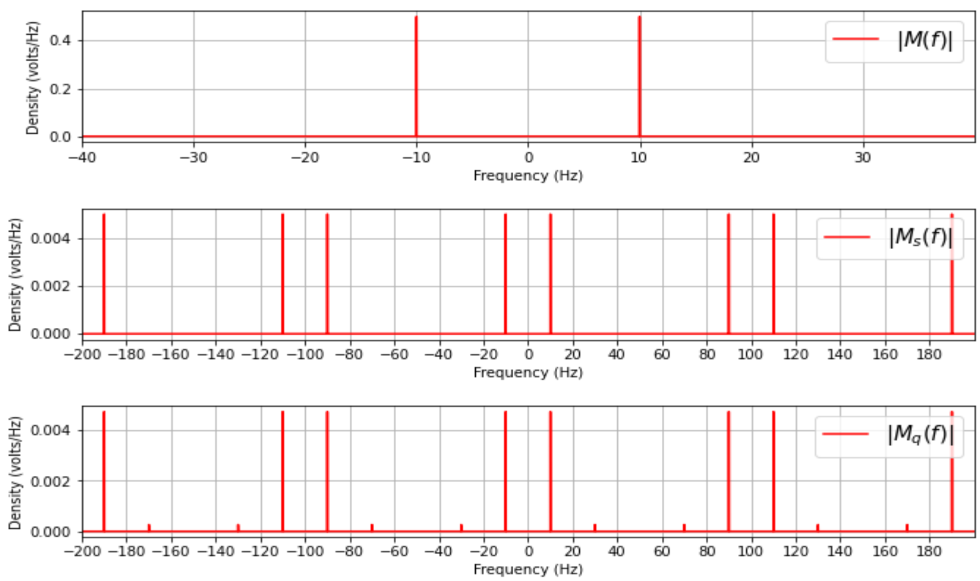

Figure 11:massage signal & sampled signal & output of quantizer in frequency domain

- **<u>Note</u>**: figure above shows the message in frequency domain in the first plot from the top, then the sampled message with Fs=100 that contain the message signal repeated every Fs as we learned in the previous experiment, then the quantized signal, in the quantized plot we can see there is some noise called error at ±(30,70,130,…), this error is out from the quantizer because of rounding some samples value to the representation levels, Fig14 shows that if we reconstruct the signal by LPF with cut-off frequency=Fs/2 we will reconstruct the message signal plus some error.

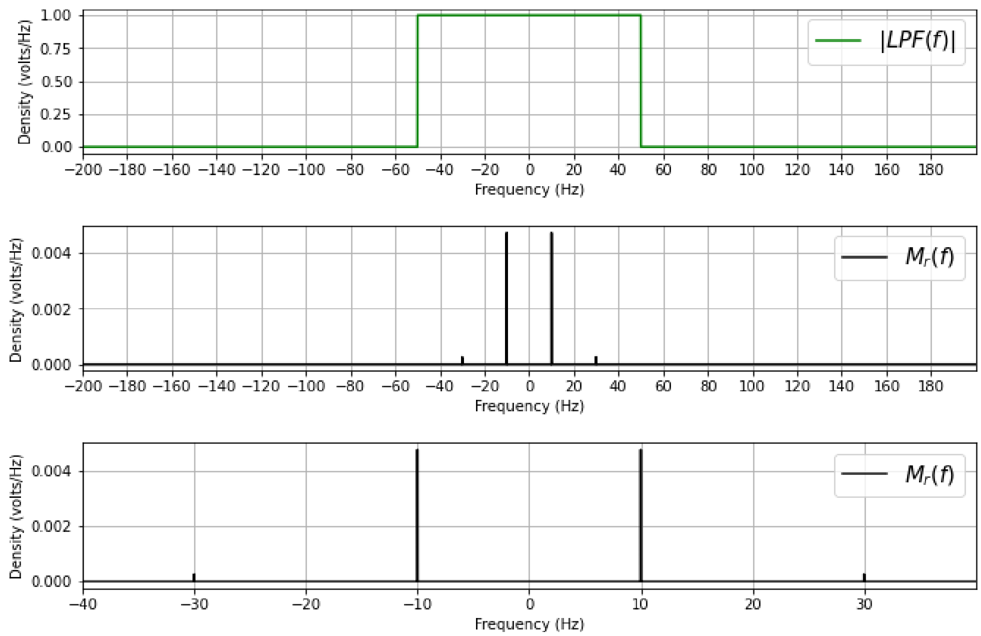

Figure 12:LPF & m^(t) & error signals in frequency domain

- **Note**: figure above shows the LPF used to reconstruct the quantized signal in the first plot from the top, then the reconstructed signal with some errors at ±(30), the last plot of this figure shows the zoomed version of reconstructed signal.

The following are some values refers to our signal:

Power of the sampled signal = 0.49999999999999956 watts

Power of the quantized signal = 0.45 watts

Power of the quantization noise = 0.0027864045000415795 watts

Signal to Quantization Noise Ratio = 179.442719100021

We can observe that almost there is no difference between Power of sampled and quantized signals, the SQNR is big which is so good.

Exercise:

1- **change number of level to 2 by let n=1:**

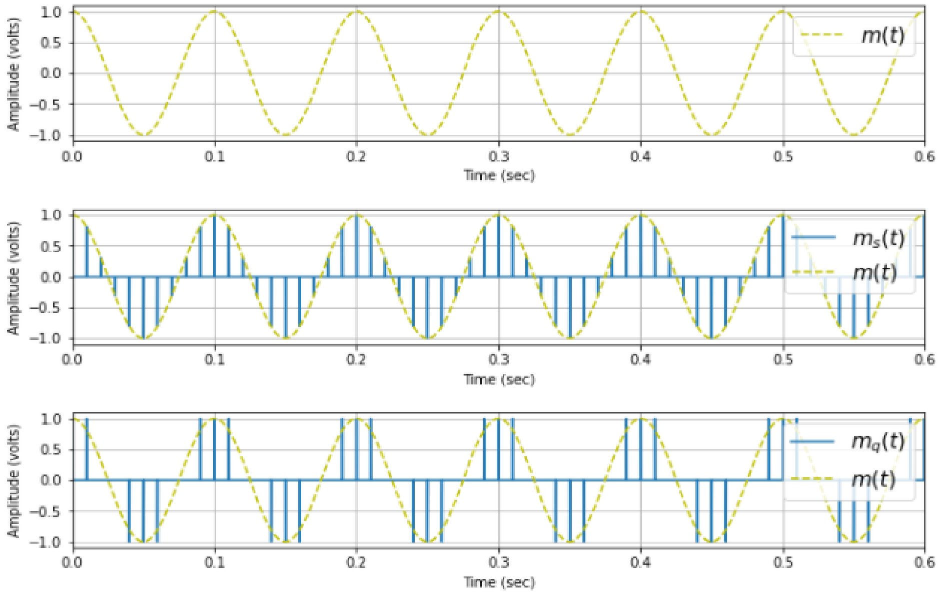

Figure 13:massage signal & sampled signal & output of quantizer in time domain when L=2

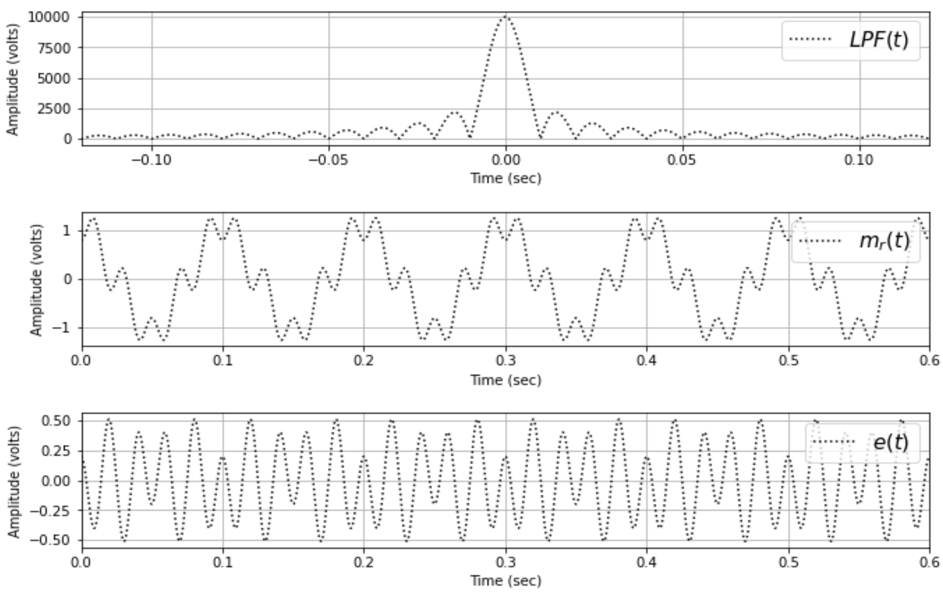

Figure 14:LPF & m^(t) & error signals in time domain when L=2

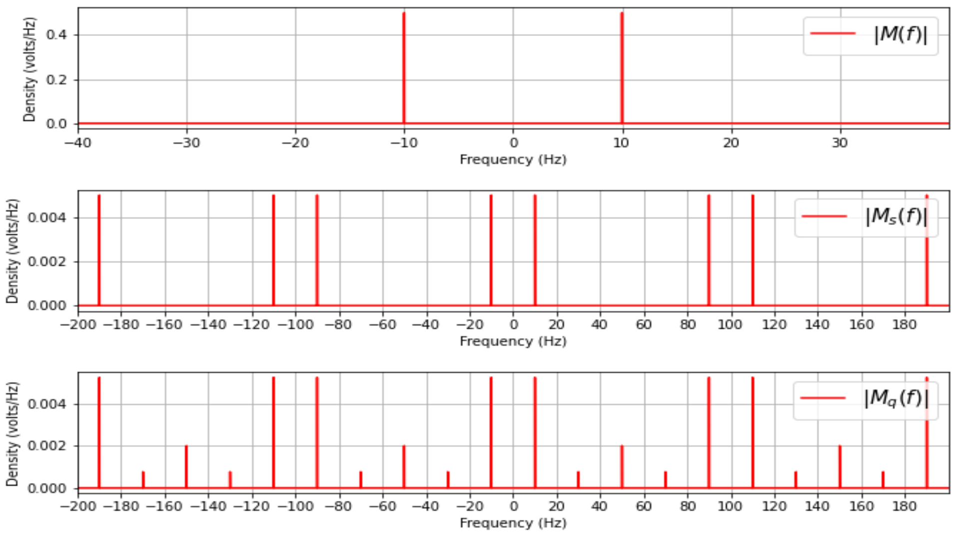

Figure 15:massage signal & sampled signal & output of quantizer in frequency domain when L=2

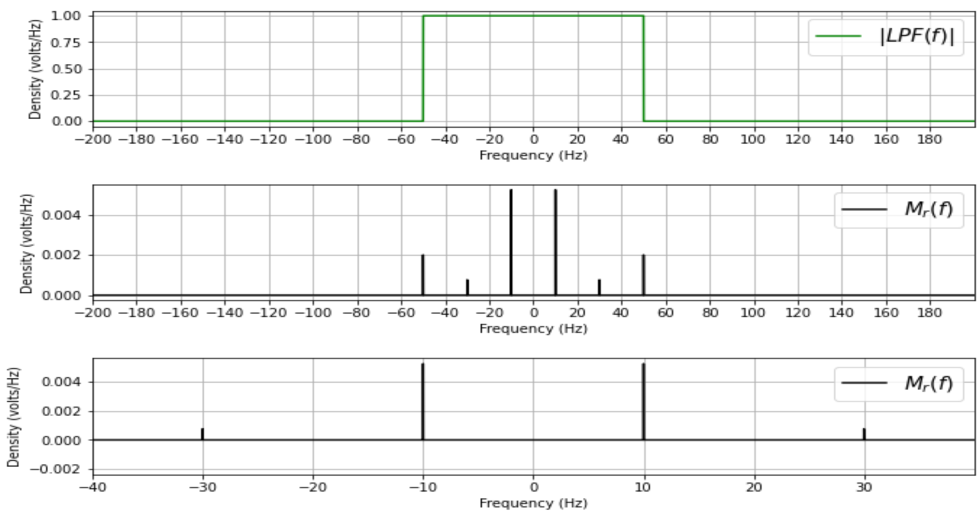

Figure 16:LPF & m^(t) & error signals in frequency domain when L=2

- **<u>Note</u>**: we notice from fig12, when change number of level the samples that we were taking from the message (part 2 from fig12) were rounded to two values. Some of them took the value 1 and some took the value 0 (part 3 from fig12) and this thing leads to:
  1- The error increased relative to the previous case, because we have reduced the number of levels.
  2- The power of the quantization noise decreased relative to the previous case.
  3- The signal to quantization noise ratio decreased relative to the previous case and this is bad thing.

Also we can see from fig12 that the difference between sampled and quantized is clear in this case, fig13 show the reconstructed signal in time domain is far from the original signal and the error is huge. Fig14 shows that the error of quantized signal in Frequency domain at ±(30,50,70,…) is huge too, fig15 shows that the reconstructed signal has a big noise at ±(30,50).So in this case I can't recovered the original massage signal.

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.6 watts
Power of the quantization noise = 0.05278640450004137 watts
Signal to Quantization Noise Ratio = 9.47213595499962
```

We can observe that the difference between Power of sampled and quantized signals is huge, the SQNR is small which is bad, so the quality is bad.

2- **change number of level to 4 by let n=2:**

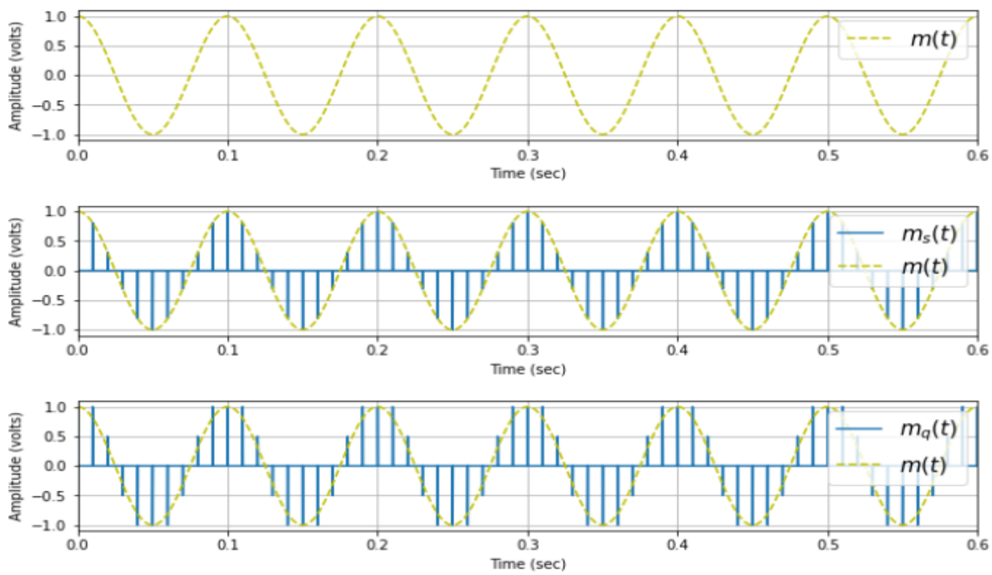

Figure 17:massage signal & sampled signal & output of quantizer in time domain when L=4

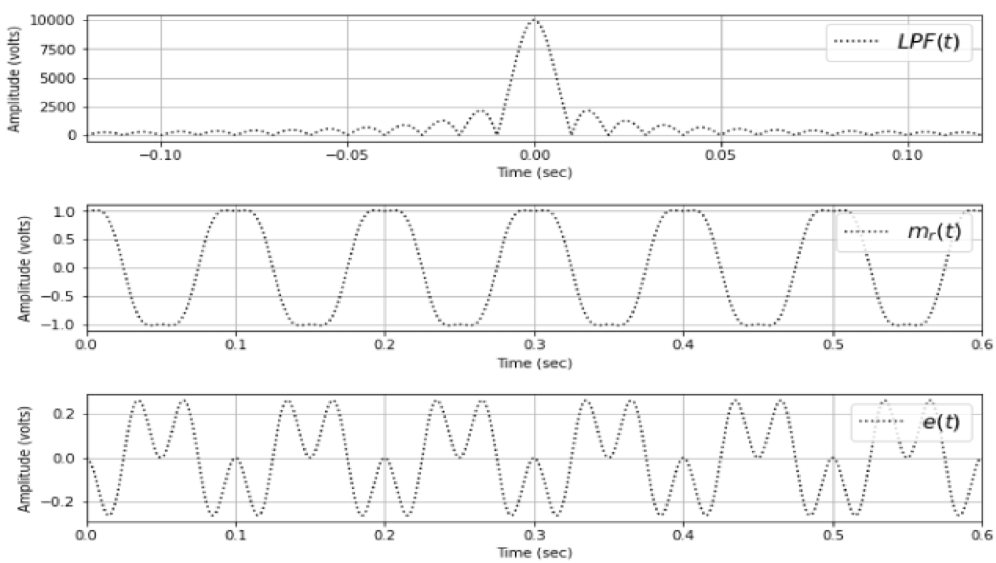

Figure 18:LPF & m^(t) & error signals in time domain when L=4

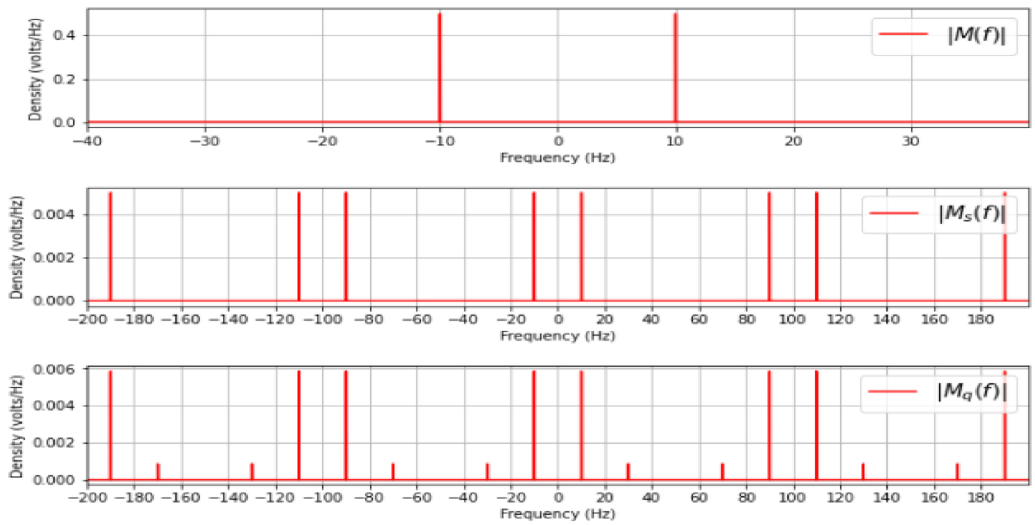

Figure 19:massage signal & sampled signal & output of quantizer in frequency domain when L=4

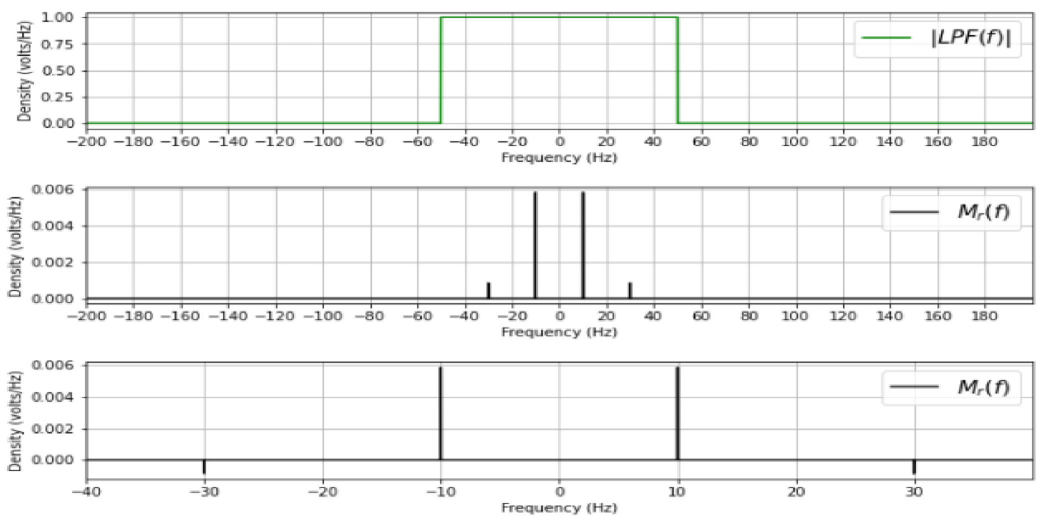

Figure 20:LPF & m^(t) & error signals in frequency domain when L=4

- **Note**: we notice from fig16, when change number of level the samples that we were taking from the message (part 2 from fig16) were rounded to many values. This show in (part 3 from fig12) and this thing leads to:
    1- The error decreased relative to the first cases because we have increase the number of levels but it's better than the previous case.
    2- The power of the quantization noise decreased, relative to the previous cases.
    3- The signal to quantization noise ratio decreased, relative to the first case and increased relative to the previous case, and, as an increase in quantization noise ratio, this is a good thing.

Also we can see from fig16 that the difference between sampled and quantized is clear in this case, fig17 show the reconstructed signal in time domain is slightly different from the original signal and the error is huge. Fig18 shows that the error of quantized signal in Frequency domain at ±(30,70,130,…) is huge too, fig19 shows that the reconstructed signal has a big noise at ±(30).So in this case I can't recovered the original massage signal.

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.7 watts
Power of the quantization noise = 0.029179606750064646 watts
Signal to Quantization Noise Ratio = 17.135254915623147
```

We can observe that the difference between Power of sampled and quantized signals is huge, the SQNR is small which is bad, so the quality is bad. But better than previous case

3- <u>change of dynamic range to [-2,2] and keep L=4:</u>

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.6 watts
Power of the quantization noise = 0.05278640450004137 watts
Signal to Quantization Noise Ratio = 9.47213595499962
```

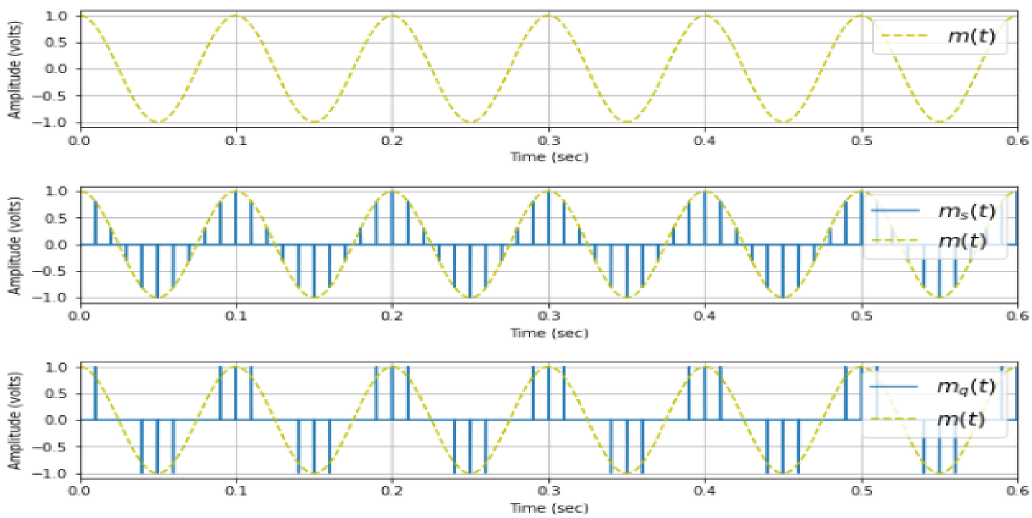

Figure 21:massage signal & sampled signal & output of quantizer in time domain when D=[-2,2]

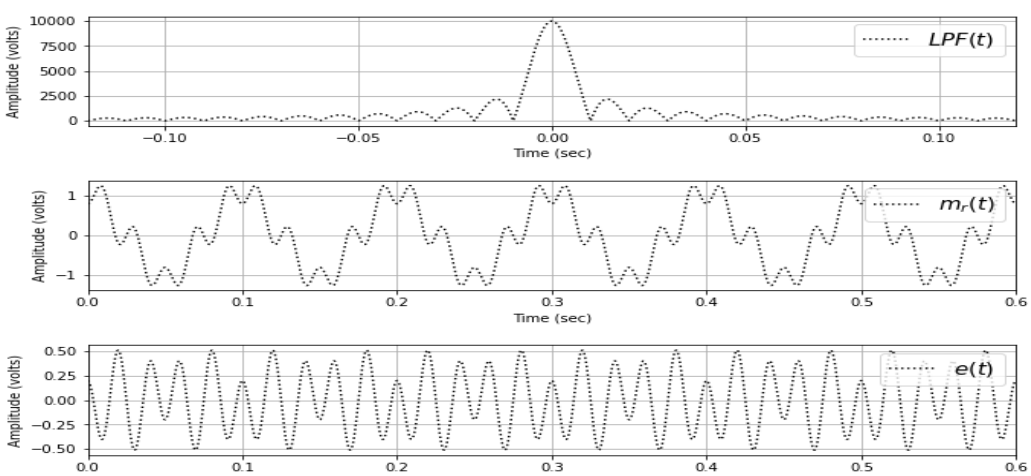

Figure 22:LPF & m^(t) & error signals in time domain when D=[-2,2]

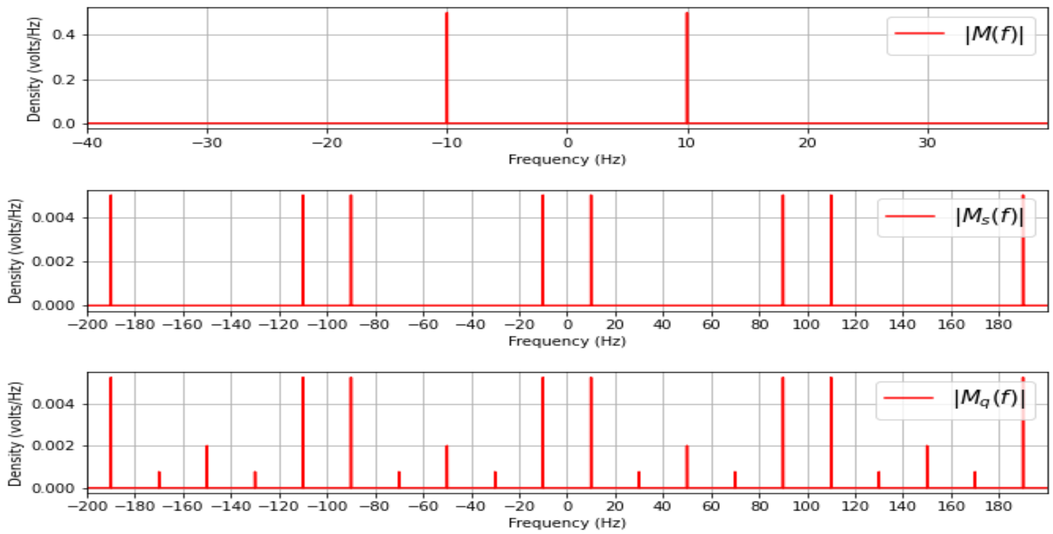

Figure 23:massage signal & sampled signal & output of quantizer in frequency domain when D=[-2,2]

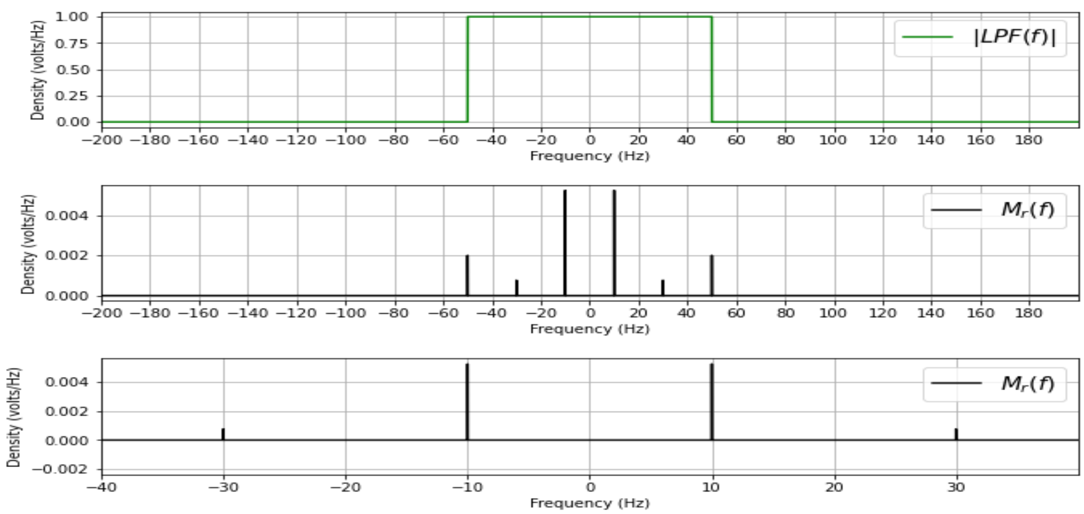

Figure 24:LPF & m^(t) & error signals in frequency domain when D=[-2,2]

- **<u>Note</u>**: we notice from fig20, when change dynamic range the error will be increased because the dynamic range between [-2,2] but the massage amplitude falls between [-1,1] and it is not compatible with the dynamic range and this thing led it to turn to weak signal. So in this case I can't recovered the original massage signal. Fig21 show the reconstructed signal in time domain is different from the original signal and the error is huge. Also The power of the quantization noise decreased relative to the first case, and The power of the quantization noise ratio decreased relative to the first case.
  In addition to, we can see from fig20 that the difference between sampled and quantized is clear in this case. Fig22 shows that the error of quantized signal in Frequency domain at ±(30,50,70,…) is huge too, fig23 shows that the reconstructed signal has a big noise at ±(30,50).So in this case I can't recovered the original massage signal.

2.5 Uniform Quantization of Weak Message Signal:

In this part, we will repeat the previous part of taking a single tune message (sine or cosine) then sample it at Fs >2W to avoid the aliasing, then we will quantize the sampled signal as we saw above then input this to LPF with cut-off = Fs/2, but in this case the dynamic range will be much more than the range where we can see the message signal.

Let us try this on same parameter of the previous, with Fm=10, Am=1, and Fs=100 which is >2W, and then apply the quantization with n=4, that leads us to have 16 levels of quantization, but the dynamic range of this case=[-10,10]. All of the process shown below, the structure of display the output will be as the previous part:

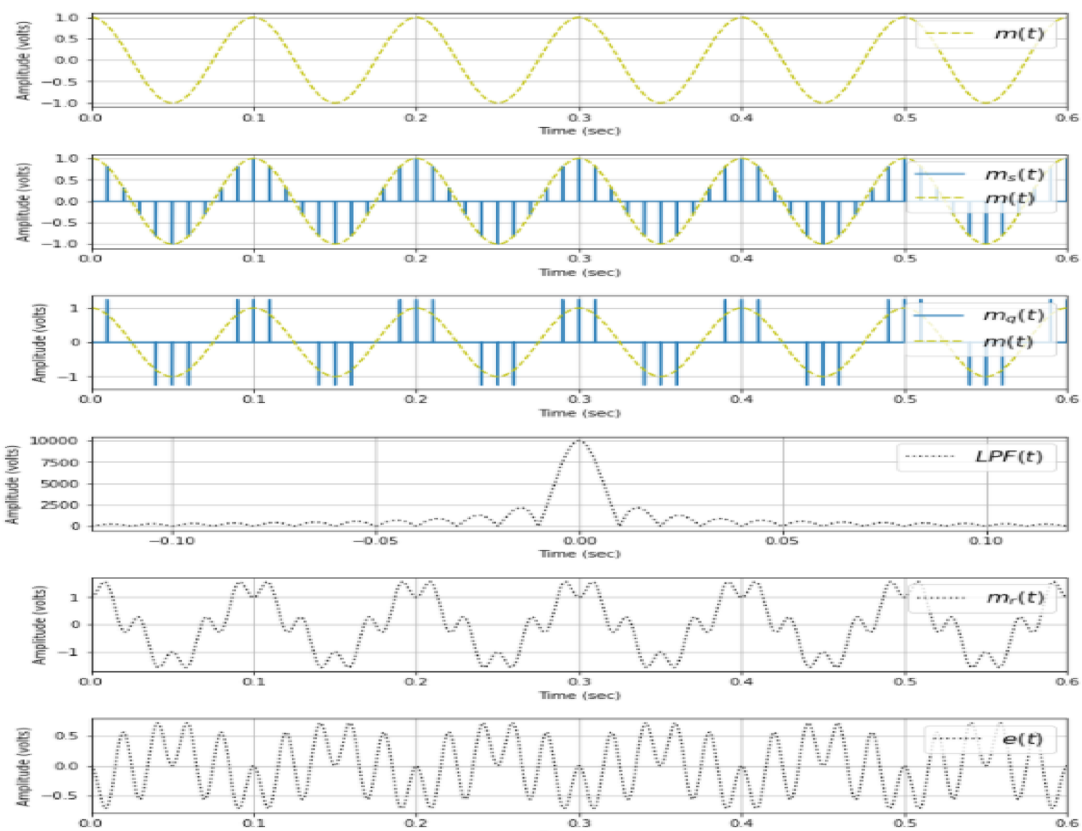

Figure 25:signal in time domain when n=4

- **Note**: The first plot of Fig24 represents the message signal, then the sampled one, then the quantized signal, even when n=4 as the previous, we can observe the big difference between the sampled and quantized signals because that the dynamic range is too big relative to the message range so the levels will be distributed throughout all the dynamic range, this will lead to that the message range covered by less number of levels and the levels will be bigger, more values of samples will be encoding to the same level, that will lead us to have more error between message and the reconstructed signals as shown in the last plot of Fig24, so we cannot reconstruct the original signal. Also The power of the quantization noise increased relative to the previous case, and The power of the quantization noise ratio decreased relative to the previous case and this is bad things.

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.9375 watts
Power of the quantization noise = 0.1284830056250528 watts
Signal to Quantization Noise Ratio = 3.891565250731502
```

We can observe that the difference between Power of sampled and quantized signals is huge, the SQNR is small which is bad, so the quality is bad.

Exercise:

1- Lets change Am to Am=9:

```
Power of the sampled signal = 40.49999999999965 watts
Power of the quantized signal = 40.3125 watts
Power of the quantization noise = 0.06327640500378133 watts
Signal to Quantization Noise Ratio = 640.0490040099372
```

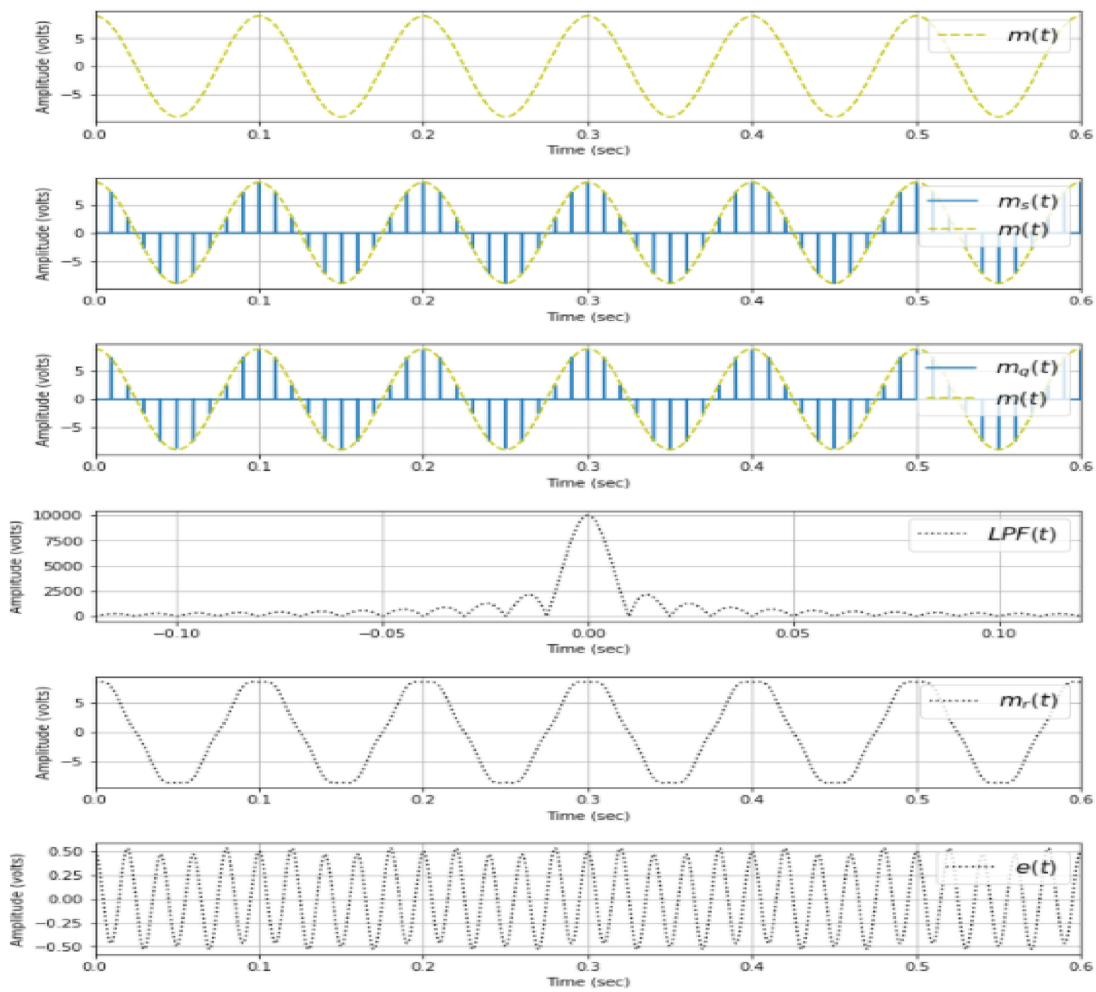

Figure 26:signal in time domain when Am=9

- **Note**: we notice from fig25, when change amplitude of the massage signal, number of level the samples that we were taking from the message (part 2 from fig25) were rounded to many values. This show in (part 3 from fig25) and this thing leads to:
  1- The error decreased relative to the previous case because we have many of levels.

2- The power of the quantization noise decreased, relative to the previous cases.
3- The signal to quantization noise ratio increased, relative to the previous case and, as an increase in quantization noise ratio, this is a good thing.

Also we can see from fig25 that the small difference between sampled and quantized is clear in this case. Therefore, almost in this case, we were able to recover the massage signal.

2- <u>Lets change n to n=8:</u>

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.489501953125 watts
Power of the quantization noise = 0.0003620830469209177 watts
Signal to Quantization Noise Ratio = 1380.8986757372274
```

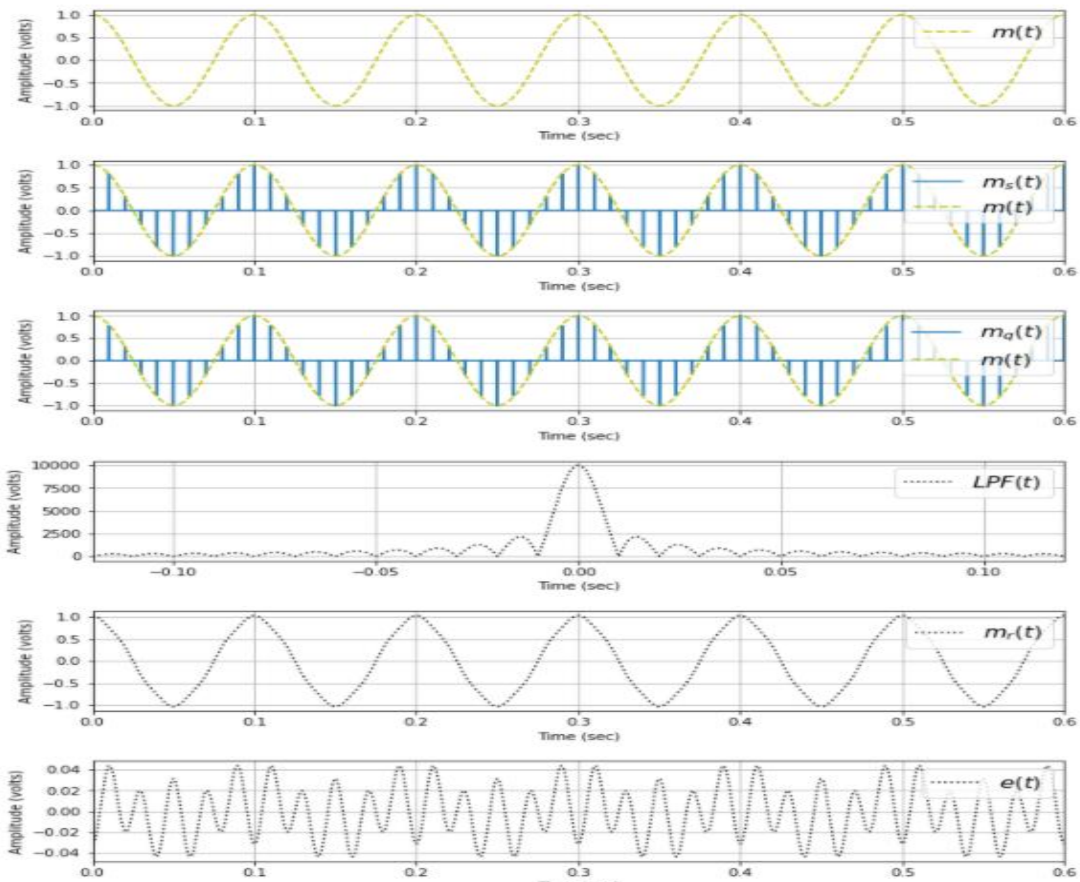

Figure 27:signal in time domain when n=8 bits

- **<u>Note</u>**: we notice from fig26, when change number of bits, then number of level the samples that we were taking from the message (part 2 from fig26) were rounded to many values. This show in (part 3 from fig26) and this thing leads to:

4- The error decreased relative to the previous case because we have many of levels.
5- The power of the quantization noise decreased, relative to the previous cases.
6- The signal to quantization noise ratio increased, relative to the previous case and, as an increase in quantization noise ratio, this is a good thing.

Also we can see from fig26 that the small difference between sampled and quantized is clear in this case. Therefore, almost in this case, we were able to recover the massage signal.

2.6 Robust (μ−Law) Quantization of a Single Tune Message Signal:

In this part, we will repeat the previous part of taking a single weak tune message (sine or cosine) then sample it at Fs >2W to avoid the aliasing, then we will quantize the sampled signal, **but in this case the quantization is based on Robust quantization not uniform like previous** (input the signal to the compressor then to the uniform quantizer then to the expander), then input this to LPF with cut-off = Fs/2 in order to reconstruct the signal.

Let us try this on same parameter of the previous, with Fm=10, Am=1, and Fs=100 which is >2W, and then apply the quantization with n=4, that leads us to have 16 levels of quantization, with μ=255, the dynamic range = [-10,10]. All of the process shown below, <u>the structure of display the output will be as the previous part</u>:

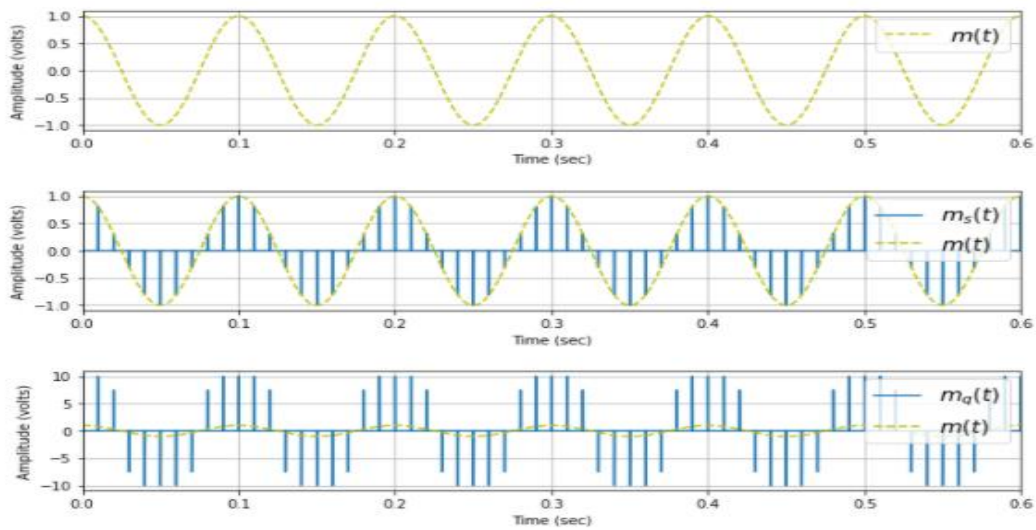

Figure 28:time domain when n=4

- **<u>Note</u>**: Fig27 shows the message signal in the first plot from the top, then the sampled signal, then the quantized signal, we can observe that the difference between the sampled and quantized is smaller than in case of uniform, and we can also notice that the mq(t) shape is close to the shape of the m(t). let's see the output when we reconstruct the signal from quantized signal in Fig28.

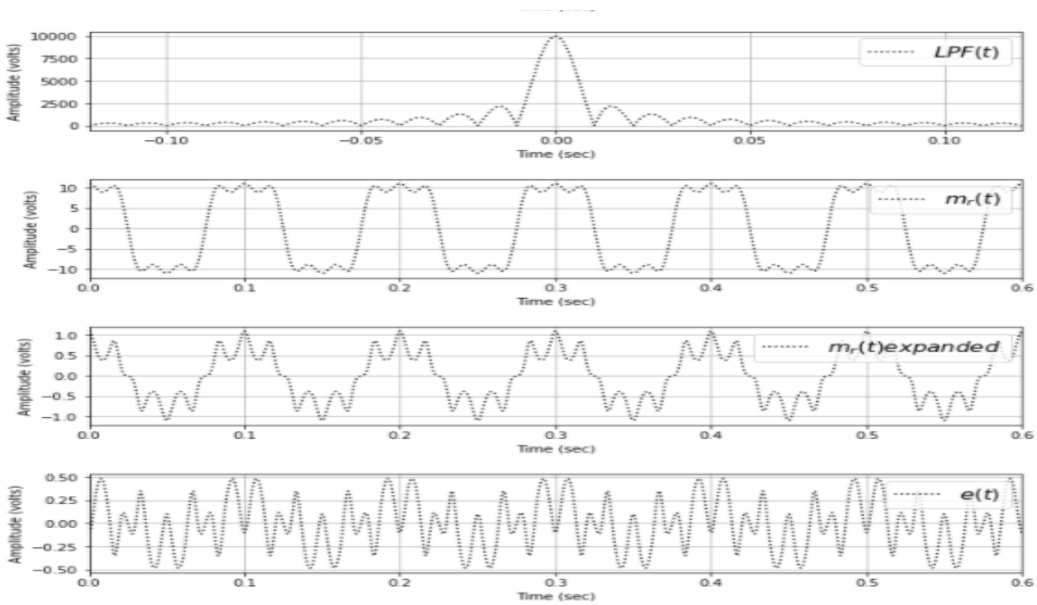

Figure 29:timed domain when n=4

- **<u>Note</u>**: Fig28 shows the LPF used to reconstruct the signal in the 1st plot, then the reconstructed signal, then the reconstructed signal after the expander, the error can be seen in the last plot, it's kind of big but still it is better than in the previous part (uniform) where the signal quantization noise ratio is better than uniform. We can observe that the difference between Power of sampled and quantized signals is huge, but smaller than the previous part, the SQNR is small which is bad, so the quality is bad. Let's see the output in the frequency domain:

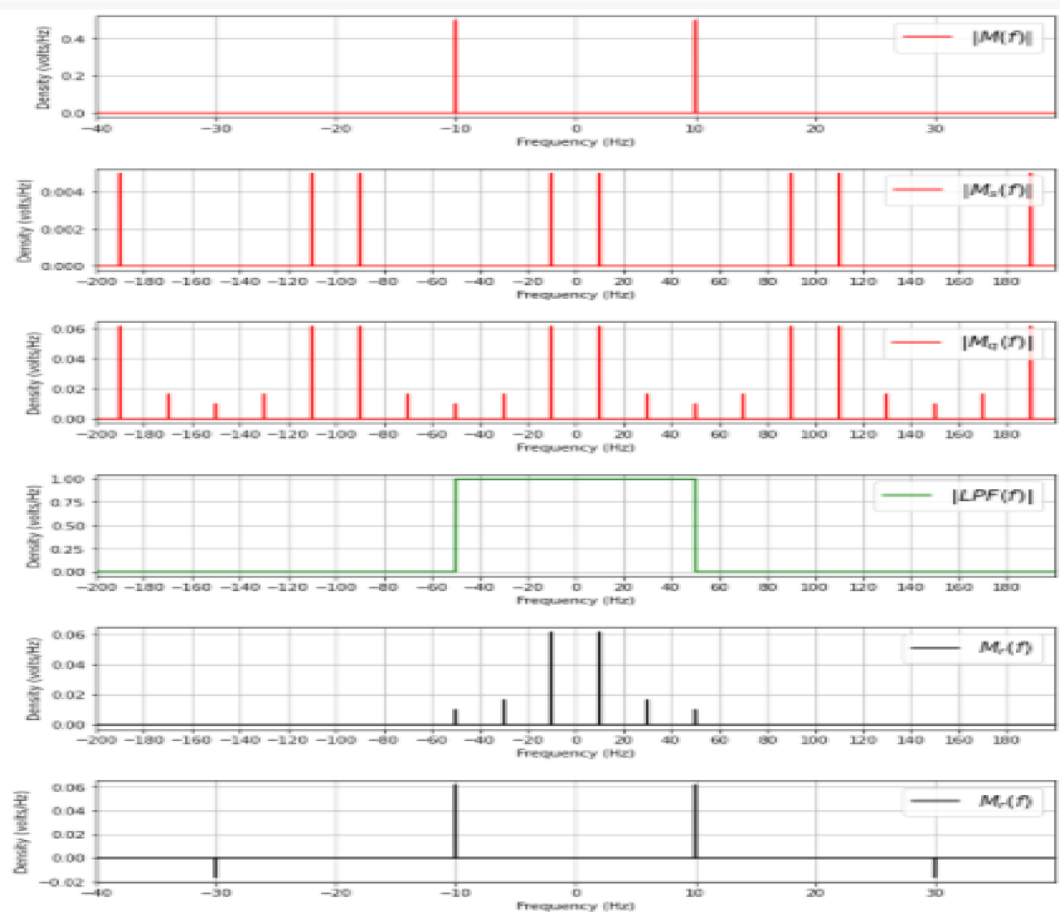

Figure 30:frequency domain when n=4

- **<u>Note</u>**: Fig29 shows the quantized signal in frequency domain in the third plot with some errors on ±(30,50,70,…), then the LPF, then the reconstructed signal with some noise at ±(30,50) but it is better than in the previous part(uniform).

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.6244152249134948 watts
Power of the quantization noise = 0.0161253293488418 watts
Signal to Quantization Noise Ratio = 31.007118625822553
```

We can observe that the difference between Power of sampled and quantized signals is huge, but smaller than the previous part, the SQNR is small which is bad, so the quality is bad.

Exercise:

1- **Let us change the number of bits used to encode the samples to n=2 to make it equal to these in the previous part so we can compare the results below:**

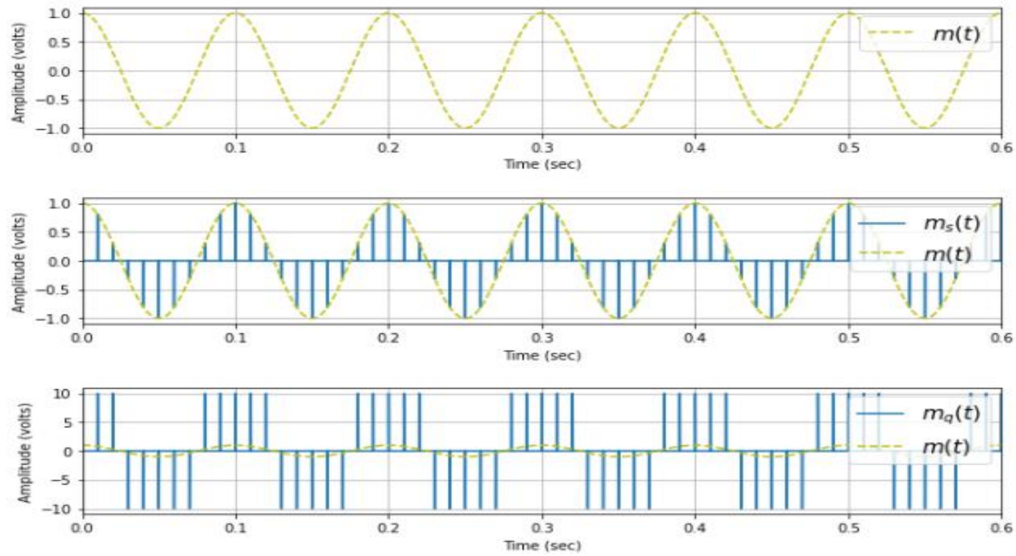

Figure 31:time domain when n=2

- **Note:** As we see from Fig30 the difference between the sampled and quantized is bigger than when n=4, but it's better than in uniform quantization.

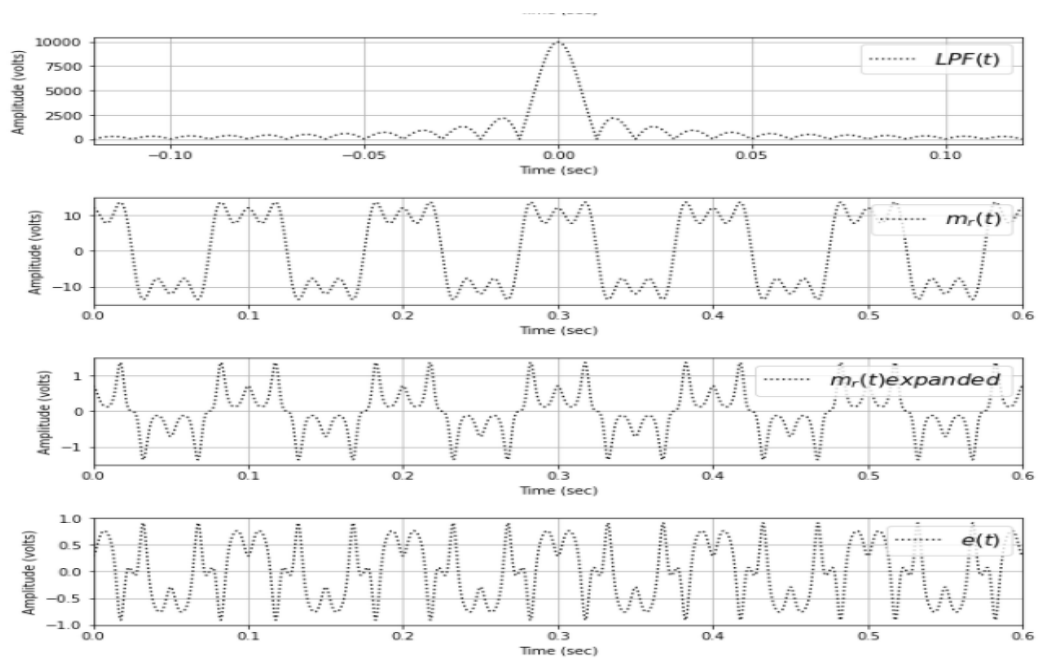

Figure 32:time domain when n=2

- **Note**: We can see that we expanded signal after reconstruction is worse than when n=4, but it's better than when we used uniform quantization.

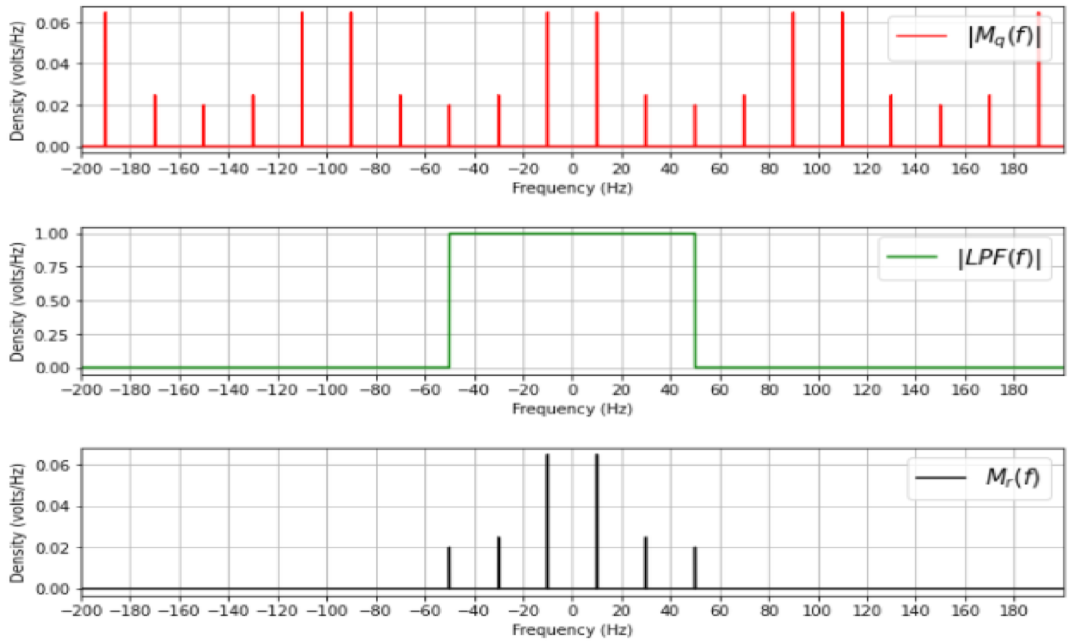

Figure 33:frequency domain when n=2

- **Note**: From Fig32 we can see that the quantized signal has errors at ±(30,50,70,…), as when n=4 but this time the amplitude of the error is bigger, then we can see the LPF in the 2nd plot, then the reconstructed signal with some noise at ±(30,50) with bigger amplitude than when n=4.

The following are some values refers to our case when n=2:

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 1.0 watts
Power of the quantization noise = 0.2055728090000879 watts
Signal to Quantization Noise Ratio = 2.4322282817071486
```

We can observe that the difference between Power of sampled and quantized signals is huge, its bigger than when n=4, the SQNR is small which is bad, so the quality is bad, worse than when n=4, better than uniform.

Conclusion: as much as the number of bits used for encoding increase the quality will increase and vice versa, and it's better than uniform quantization when we encode at the same number of bits.

2- **<u>If we changed μ value to 5 instead of 225 with same parameters as in the start of this part, the situation of the quality will get better, you can observe that from figures below:</u>**

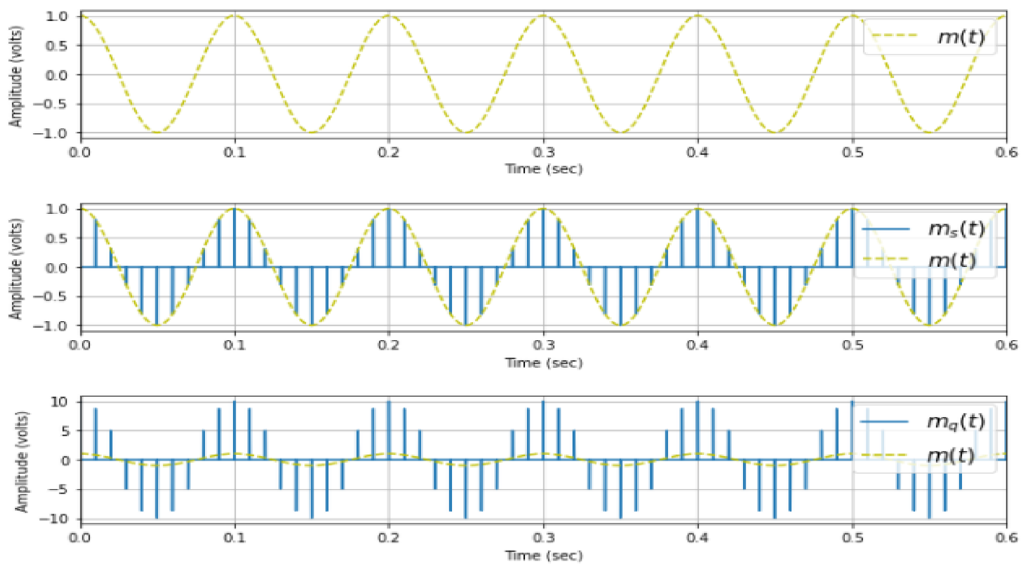

Figure 34:time domain when μ=5

- **<u>Note</u>**: As we see from Fig33 the difference between the sampled and quantized is smaller than when μ=225.

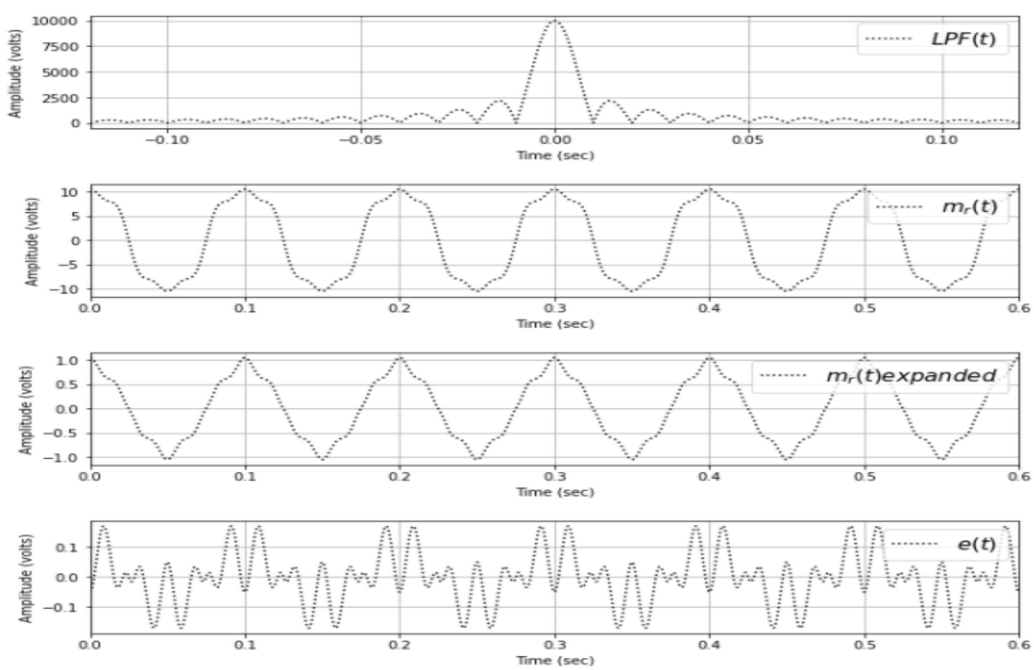

Figure 35:time domain when μ=5

- **<u>Note</u>**: Fig34 above shows that the expanded signal after reconstruction is worse than when μ=225.

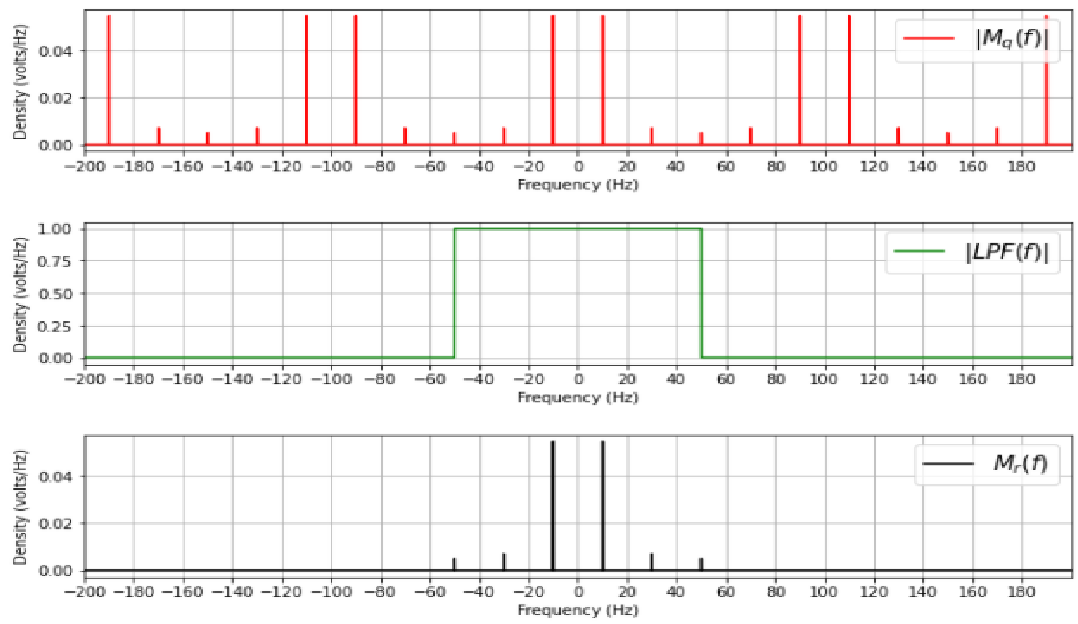

Figure 36:frequency domain when μ=5

- **Note**: From Fig35 we can see that the quantized signal has errors at ±(30,50,70,…), as when μ=225, but this time the amplitude of the error is smaller, then we can see the LPF in the 2nd plot, then the reconstructed signal with some noise at ±(30,50) with smaller amplitude than when μ=225.

The following are some values refers to our case when μ=225:

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.4641744361712346 watts
Power of the quantization noise = 0.0011386293547648756 watts
Signal to Quantization Noise Ratio = 439.12445951584
```

We can observe that the difference between Power of sampled and quantized signals is small, its smaller than when μ=225, and smaller than the uniform quantization, the SQNR is big which is good, so the quality is fine, better than when μ=225, better than uniform.

Conclusion: as much as μ value decrease the quality will increase and vice versa

3- **<u>Let's modify the main example and change the dynamic range to be [-1,1] with the same rest parameters, and see what will be happened below:</u>**

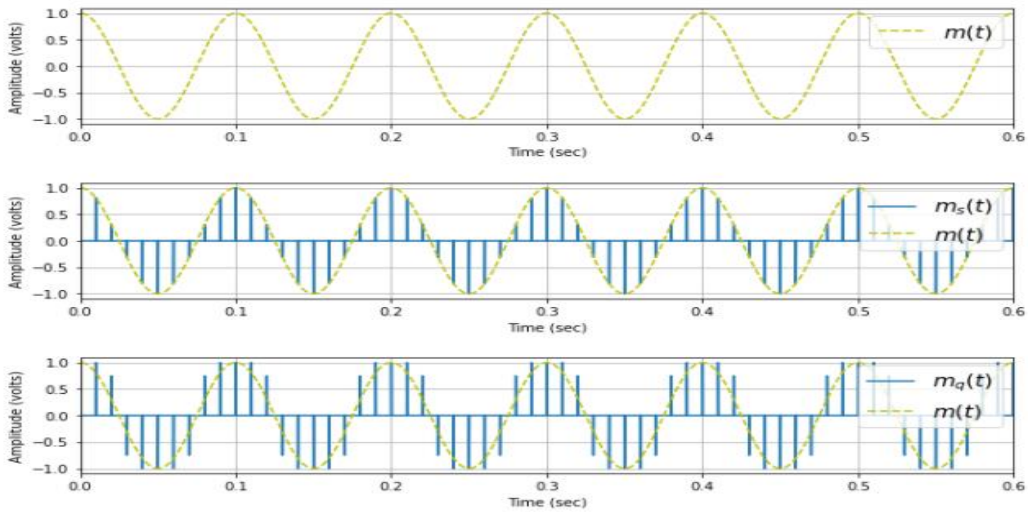

Figure 37:time domain when DR=[-1,1]

- **<u>Note</u>**: As we see from Fig36 the difference between the sampled and quantized signals almost remains the same as when DR= [-10,10].

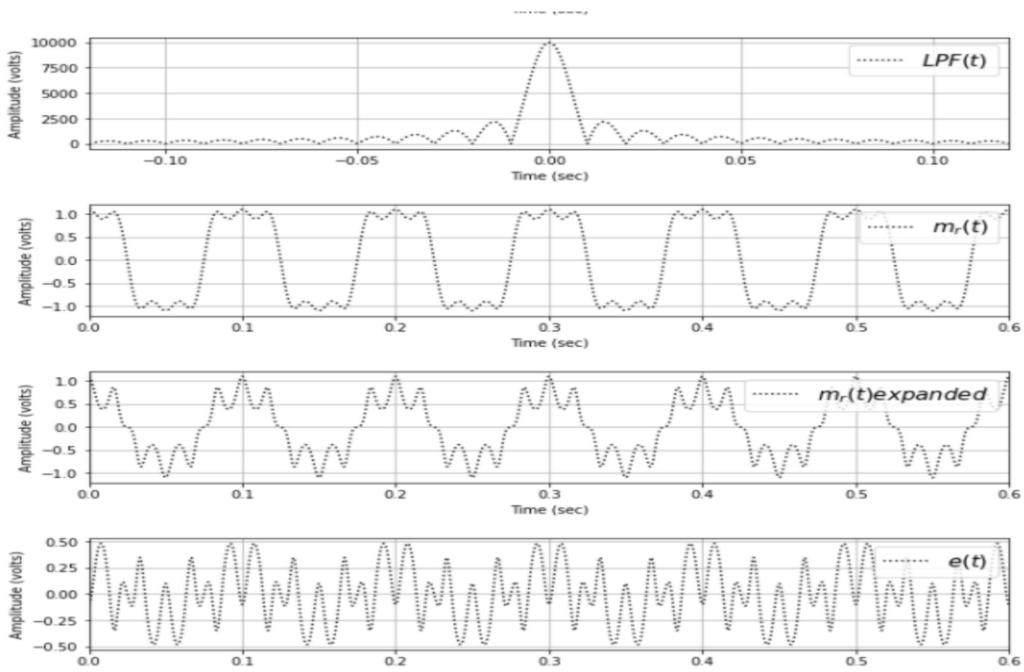

Figure 38:time domain when DR=[-1,1]

- **<u>Note</u>**: Fig37 shows that the error signal almost remains the same as when DR=[-10,10].

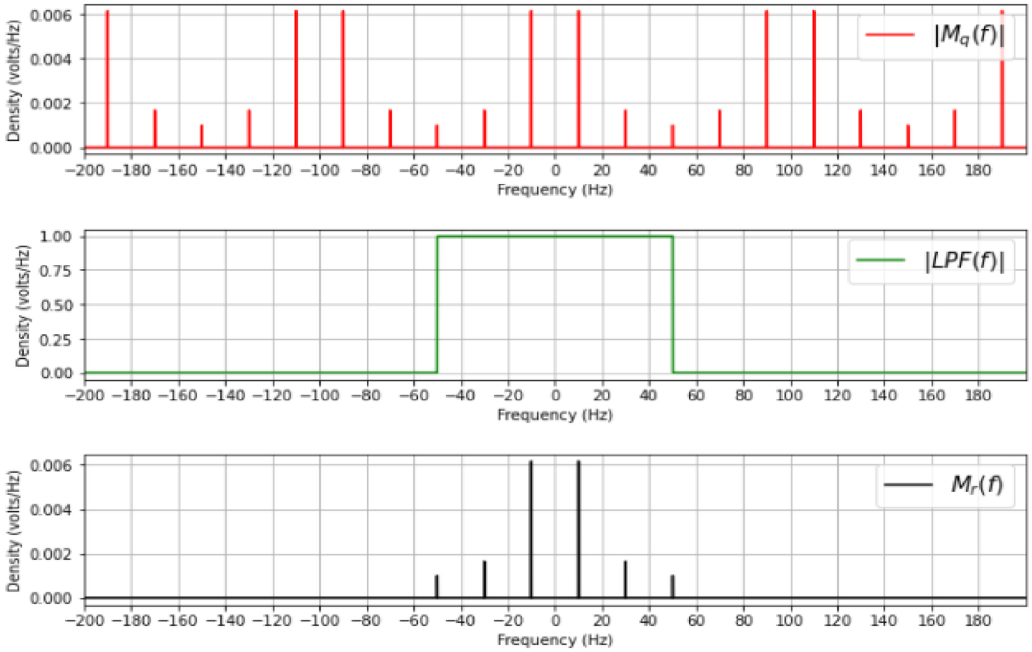

Figure 39:frequency domain when DR=[-1,1]

- **Note**: From Fig38 we can see that the quantized signal has errors at ± (30,50, 70, …) with same amplitude values, as when DR= [-10,10].

Conclusion: the dynamic range of the quantizer doesn’t affect much the message in this quantization method.

The following are some values refers to our case when DR= [-1,1]:

```
Power of the sampled signal = 0.4999999999999956 watts
Power of the quantized signal = 0.6244152249134948 watts
Power of the quantization noise = 0.0161253293488418 watts
Signal to Quantization Noise Ratio = 31.007118625822553
```

We can observe that the power of sampled, quantized, quantization noise, the SQNR ratio almost remain the same as when DR= [-10,10].

2.7 Quantization of Real Audio Signal:

In this section will investigate the quantization of real audio signals using uniform quantization and robust quantization, and then we will see how varying of some parameters can affect the quantized signal.

Because of the signal is already sampled on Fs=44100, we read the samples of this signal, and then the maximum sample was founded which is = 25843, in order to make the dynamic range covers all the range of samples. We listened to the original loaded signal.

Based on the maximum value of the audio signal (25843), we will set the dynamic range of the uniform quantizer to be = [-26k,26k], we adjust the number of bits used to encode the quantized values to 4 so we will have 16 quantization level, then we apply the sampled signal to this uniform quantizer. After that we listened to the quantized signal and we note the output has poor quality, it has a lot of noise, to describe the quality let us see the following values about this quantized signal:

```
Power of the sampled signal = 50.80288707116384 watts
Power of the quantized signal = 51584743.57902732 watts
Power of the quantization noise = 772421.9493927296 watts
Signal to Quantization Noise Ratio = 6.577090036230141e-05
```

The most important value is the SQNR, that will index to the quality of the quantized signal, as we see above the SQNR is too small, that will confirm to us about to poor quality.

After that we applied robust quantization to the same signal with µ=225, and n=4, the quality of this quantized signal is almost equal to that of the uniform, it has a lot of noise, you can see the values below:

```
Power of the sampled signal = 50.80288707116384 watts
Power of the quantized signal = 52622390.21877491 watts
Power of the quantization noise = 1963730.3336284335 watts
Signal to Quantization Noise Ratio = 2.5870602598114414e-05
```

All the values almost equal to the values of uniform quantization.

Exercise:

1- **Let's repeat the entire section with n=16 this time and see the values below:**

A) **Uniform values and output:**

```
Power of the sampled signal = 50.80288707116384 watts
Power of the quantized signal = 51983563.639390975 watts
Power of the quantization noise = 0.05234553085755013 watts
Signal to Quantization Noise Ratio = 970.5295989721769
```

We listened to the quantized signal and note it's almost similar to the original, this can be confirmed by the big value of SQNR.

B) **Robust values and output:**

```
Power of the sampled signal = 50.80288707116384 watts
Power of the quantized signal = 51983623.93617684 watts
Power of the quantization noise = 0.12845613932194955 watts
Signal to Quantization Noise Ratio = 395.4881980676423
```

The quality of the quantized signal is enough and almost similar to the original signal, this can be confirmed by the big value of SQNR relative to when n=4.

2- **Now, let's change the DR to [-3k,3k], n=4 and see the results below:**

A) **Uniform values and output:**

```
Power of the sampled signal = 50.80288707116384 watts
Power of the quantized signal = 51990208.801254064 watts
Power of the quantization noise = 12036.312183842221 watts
Signal to Quantization Noise Ratio = 0.004220801711953152
```

Surprisal things happened, the quality of the quantized signal get better, almost it's equal to the original, this can be confirmed by the big difference of the SQNR.

B) **Robust values and output:**

```
Power of the sampled signal = 50.80288707116384 watts
Power of the quantized signal = 52622390.21877491 watts
Power of the quantization noise = 1963730.3336284345 watts
Signal to Quantization Noise Ratio = 2.58706025981144e-05
```

Here the quality of the signal remained as when DR=[-16k,16k], there is no difference in the quality of the signal, the SQNR remained the same.

3. Conclusion:

In conclusion, we were able to understand the Working mechanism of Pulse Code Modulation (PCM) and understand the different between another type of quantization (uniform quantizer and robust quantizer). Also, we were able to understand the effect of changing the parameters on the recovered signal. We were able to understand the purpose of using different quantizer on the type of the signal. Finally, the experiment ran smoothly using the Colab and our results were logical and convincing.