Comparing the Performance of a Matched Filter and Majority Voting to Cope with Harsh Electromagnetic Disturbances

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***Abstract*—This paper compares the effectiveness of two techniques that can be implemented at the receiver side in digital communication channels to cope with harsh EMI. The techniques are applying majority voting or a matched filter to the same oversampled values of the receiving encoded bit stream. After applying one of both techniques, the determined bits are compared with the bits that were originally sent and a bit-error-rate is calculated. The filter or voter gain, which is the difference in signal-to-noise ratio required to achieve the same bit-error-rate, is used as metric to quantify the performance of both techniques. The numerical results show that using a matched filter results in a higher gain than using any majority voting technique. However, using the majority voting technique allows the receiving end to have an idea if something went wrong, allowing the system to perform a safety procedure.**

***Index Terms*—EMI Resilience, bit-error-rate, matched filter, majority voting, digital signal processing**

I. Introduction

Observing the technological advances that have happened in the last years, one can decide that the digital revolution is still ongoing and increasing exponentially. The amount of electrical systems, sensors, Internet-of-Things (IoT) devices and new wireless networks in all their forms and shapes is getting larger and larger. Most of these systems include some communication channel to connect and interact with other smart devices, infrastructure or even the cloud or fog. The communication protocols that are used in these system have to be reliable, robust and be resilient against Electromagnetic Interference (EMI). The state-of-the-art of EMI resilience has expanded during the last years. The IET Code of Practice [1] and the guidance document IEEE 1848 [2] introduce techniques and measures (T&Ms) for software and hardware implementations. The software techniques comprise, amongst others, improved error detection and correction codes that are commonly used in digital communications. The hardware techniques consist of, amongst others, inversion [3], spatial [4], [5] and time [6] diversity. All of these cope with electromagnetic disturbances by introducing redundancy techniques that are electromagnetic (EM) diverse. Another well known technique to improve the robustness against noise is by adding a matched filter to the receiver [7].

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The literature describes that a matched filter performs well for stochastic or random noise such as Additive White Gaussian Noise (AWGN) and that it is commonly used to reduce the bit-error-rate (BER) for a certain signal-to-noise ratio (SNR). In [8], the performance of a matched filter was investigated when exposed to a harsh continuous wave disturbance. The results showed that a matched filter is most effective when the frequency of the continuous wave (CW) disturbance lays around an integer multiple of the bit frequency or when the frequency of the CW disturbance is significantly larger than the frequency of the transmitted signal.

A commonly used communication protocol in a lot of wired and wireless systems is the universal asynchronous receiver-transmitter (UART) protocol. This protocol allows communication between two devices without additional clock [9]. The system that receives communication via the UART protocol will oversample the incoming signal. In its most basic form it uses the sample in the middle of one received symbol to decode it to a binary value. Additionally, advanced UART modules allow us to use a subset of those samples to perform majority voting [9]. Mostly three sampled values are used

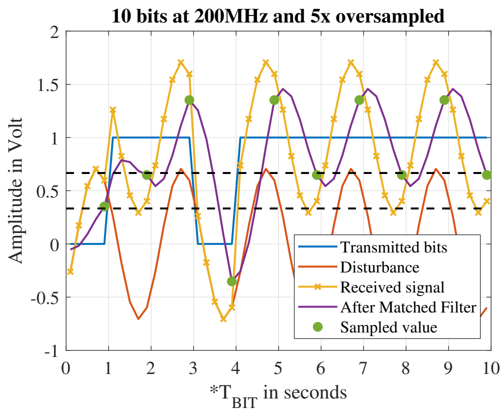


Fig. 1: NRZ-L encoding of 10 bits ('0110111111'), transmitted at a bitrate f_{BIT} of $200\,\text{MHz}$, oversampled $M = 5$ times and disturbed by a $500\,\text{MHz}$ disturbance. The black dashed lines represent the decoding thresholds. The result from a matched filter and majority voter would be 'xx101x1x1x' and '1010101010' respectively, where 'x' denotes a faulty bit, both resulting in a BER of 40%.

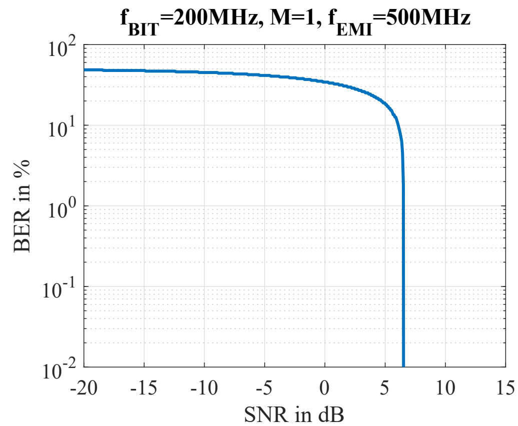


Fig. 2: BER in function of SNR when using no oversampling at a bit rate $f_{\text{BIT}} = 200$ MHz and an EMI frequency of $f_{\text{EMI}} = 500$ MHz.

to perform majority voting on, although in advanced UART modules using more samples is possible.

Using the information from the matched filter and the EMI resilience techniques, we want to compare the performance of a matched filter against the performance of majority voting while subjected to harsh EMI, in this case purely sinusoidal continuous wave EMI.

This paper is organised as follows. Section II describes the two investigated techniques to improve EMI resilience. In Section III the used communication channel setup which incorporates the creation of the disturbance signal is briefly described. Section IV explains how the BER, the filter gain and voter gain are calculated. Next, Section V discusses the numericals results of both techniques and compares them. Finally, the findings are concluded in Section VI.

II. Theory of Receiver Techniques

Many receivers in communication channels oversample the receiving signal to perform some processing operation to improve the certainty of determining the right received bit and thus decrease their BER. In the following subsections the theoretical background of a matched filter and majority voting are briefly described.

A. Matched Filter

The theory of a matched filter has already been extensively explained in [7], [8] and is briefly repeated here for completeness of the paper. In digital communication systems and digital signal processing, a matched filter is often used to maximise the SNR of the receiving signal. Doing so, it minimizes the BER to get the maximum performance out of the communication system. The matched filter makes use of the property that the incoming noise is random or stochastic and that it has an average time domain value that is equal to zero. A common example is Additive White Gaussian Noise (AWGN), which represents thermal noise as can be found in almost any component or system. The implementation of such a matched filter can be done in several ways.

The first implementation method is by using the matched filter as a linear filter, where the filter uses the signature (or waveform) s_1 of the required signal (in this case the waveform of a digital '1'). The impulse response or transfer function h of the filter is found by inverting the signature in time and performing a complex conjugate (indicated with *) on s_1.

$$h[m] = s_1[T - m]^* \tag{1}$$

In (1), m indicates the index of the sample in one bit. The amount of samples M are uniformly distributed over the bit period, e.g. for $M = 4$ the bit is sampled at $t = [1/4T_{\text{BIT}}; 1/2T_{\text{BIT}}; 3/4T_{\text{BIT}}; T_{\text{BIT}}]$. In Linear Time Invariant systems like this, the filter is applied by performing a convolution of the transfer function h with the received signal x:

$$y[k] = \sum_{m=0}^{M-1} h[k-m]x[m] = (h * x)[k]. \tag{2}$$

In (2), x exists out of the superposition of the desired encoded signal and the disturbance, which is further explained in Section III.C. Because of this superposition, distributivity can be applied resulting in two separate convolutions with the transfer function of the filter. Once with the desired signal and once solely on the disturbance. The convolution with the desired signal results in the exact bit stream, while the convolution with the disturbance calculates in essence the average of the sampled disturbance. Afterwards both are added up. This explains why a matched filter is so effective for Gaussian noise, indeed because the average is almost zero.

The second method of implementing a matched filter uses the same reasoning, but is done by only adding and multiplying

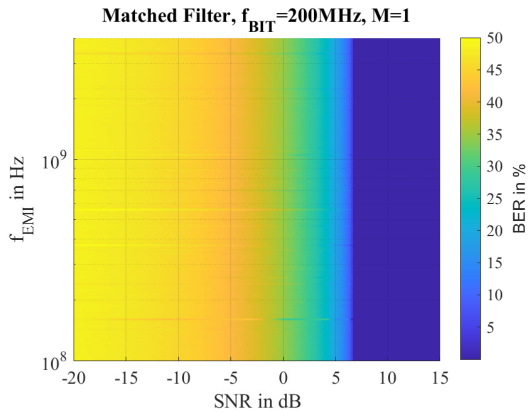


Fig. 3: BER in function of SNR when using no oversampling at a bit rate $f_{\text{BIT}} = 200$ MHz showing no influence of f_{EMI}.

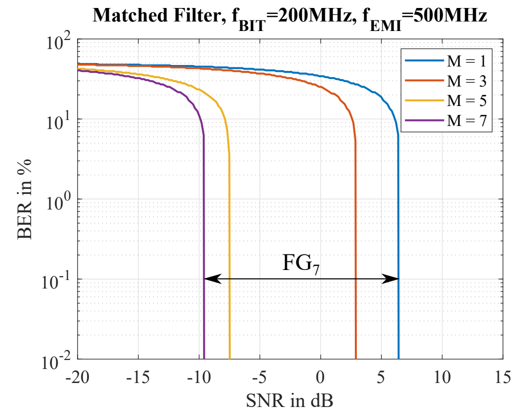


Fig. 4: Definition of filter gain for $M = 7$.

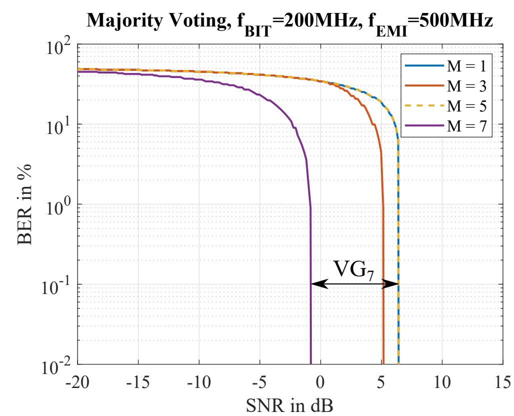


Fig. 5: Definition of voter gain for $M = 7$.

the received samples at the end of every received bit as is visible in (3):

$$y[T_{\text{BIT}}] = \frac{1}{T_{\text{BIT}}} \sum_{m=0}^{M-1} s_1[m]x[m]. \tag{3}$$

This results in an easier implementation in programmable hardware, because it only uses addition and multiplication blocks. The received disturbed sample values in one bit period are multiplied with the signature of the matched filter, added up and multiplied with a factor, to average the outcome. Again, the sum of the samples results in a minimisation of the stochastic or random noise because the average of those types of noise is near-zero. This method is also known as the matched correlator, the received signal is correlated with the signature of an encoded '1' [7], [8]. The last method is equal to the first method, but instead of applying the linear filter in the time domain, it is now used as frequency domain filter. Therefore, the Discrete Fourier Transform (DFT) of s_1 is taken and multiplied with the DFT of the received signal. An extra inverse DFT is used to convert back to the time domain and sampled at the bit frequency, and decode those values to get the received bits. In this paper the first method (convolution in time domain) is used at all times to calculate the received values after the matched filter.

B. Majority Voting

As stated in the introduction, majority voting is also used in digital communication channels to improve the reliability of the communication. The majority voting technique requires less mathematical calculations then the matched filter. Instead of using the analogue values and apply a filter, it requires that the receiver first decodes the received oversampled signals. The decoded values are then evaluated to create one single output. That evaluation happens by using binary operators that will decide if a '0' or a '1' has the majority and is called voting. It seems logical to only use odd samples, because in the case of an even number of samples the situation could occur in which there is an equal amount of ones and zero, making it impossible for the voter to decide. However, in the case of even samples per bit, also the majority is chosen. In the case of equal amounts of ones and zeros, a random output, a one or a zero can be chosen, specified by the hardware. In the case of $M = 5$ the majority voting scheme is 3oo5. The majority voting system can inform the user if it was 100% certain about its decision or not. This allows the user to create a system than can adjust the safety measures when the voter is not totally certain about its decision. Even in the special case of 2oo2 which will have the same result as 1oo1, the voter is able to inform its uncertainty. This is not further implemented in this paper but has been extensively discussed in [10].

III. Communication Channel Setup

The communication setup consists of a transmitter and receiver which interact with each other using a communication medium which could be, amongst others, a micro strip on a PCB, a cable etc. In this case, the medium is replaced by an ideal transmission line. The first part of this section describes how the bits are encoded into voltages before transmission. Following up, the considered disturbance that will alter the received voltages is explained. Finally, the receiving end where the techniques from Section II are implemented is described.

A. Transmitter

The bit stream generated by the sender uses Non-Return-to-Zero-Level (NRZ-L) encoding. This means that a digital '0' is translated to $0\,\text{V}$ and a digital '1' is translated to $1\,\text{V}$. A set of 100 random bits is encoded and transmitted at a transmission speed of f_{BIT} meaning a bit is received every bit-period T_{BIT}. The matched filter and voting technique require that the receiver oversamples the incoming signal, which is specified by the oversampling factor M. An example of 10 transmitted bits that have been oversampled 5 times is shown in Fig. 1.

B. Harsh EM Disturbance

The harsh EM disturbance considered in this paper is a continuous wave purely sinusoidal disturbance as was also the case in [8]. The induced voltage is described as:

$$V_{\text{EMI}} = A_{\text{EMI}} \sin\left(2\pi f_{\text{EMI}} \left(t - \Delta t\right)\right) \tag{4}$$

where A_{EMI} is the EMI wave amplitude, f_{EMI} is the sine wave frequency and Δt is the moment in time when the disturbance hits the communication channel. This moment in time is random and uniformly distributed between 0 and T_{EMI} so no specific induced voltage gets privileged.

C. Receiver

At the receiver both the encoded bits that are transmitted and the induced disturbance signal come together. Both signals are superposed witch each other and are sampled at the specified sample rate $f_s = M f_{\text{BIT}}$. The matched filter is applied to the incoming oversampled signals and the output of the matched filter after each bit period T_{BIT} is decoded to a digital value using the thresholds specified in Fig. 1. The threshold to determine a digital '0' is equal to 1/3 of $1\,\text{V}$, while the threshold to determine a digital '1' is equal to 2/3 of $1\,\text{V}$. If the value is located between the thresholds, the bit is determined as a faulty bit, to create a worst case BER. The same reasoning is used for the majority voting technique, but now first all the received oversampled signals are decoded to digital values. Next, the majority voting technique is applied to determine one bit as outcome. An example of the received, disturbed and sampled signals is shown in Fig. 1.

IV. Calculation of the Bit-Error-Rate and Filter Gain

The BER is considered as the metric to evaluate the effectiveness of the matched filter and the majority voter. The BER is calculated as the amount of wrongly decoded or voted bits compared to the total amount of transmitted bits. Furthermore, the filter gain is calculated by determining two things. First, the BER of interest has to be chosen to know the filter gain for that BER. In this paper the BER of interest is equal to 0.1%. Next, the minimum SNR required to generate that amount of bit errors is determined and is considered as the reference SNR. The SNR is calculated using the root-mean-square (RMS) values of both the transmitted signal and the disturbance:

$$\text{SNR} = 20 \log_{10}\left(\frac{V_{\text{BIT,RMS}}}{V_{\text{EMI,RMS}}}\right) \tag{5}$$

Finally, the matched filter or majority voter is applied, and again the minimum SNR that is required to generate a BER equal to 0.1% is calculated. Then, the filter gain and voter gain are determined by subtracting the SNR after filtering or voting from the reference SNR. This is visually shown in Fig. 4 and 5.

V. Numerical Results

First, a baseline is calculated where the bit stream is disturbed and no filter or voting technique is applied. Next, the performance of the matched filter and majority voter are compared under different properties of the CW disturbance. And finally, the filter and voting gain are compared for different disturbance frequencies.

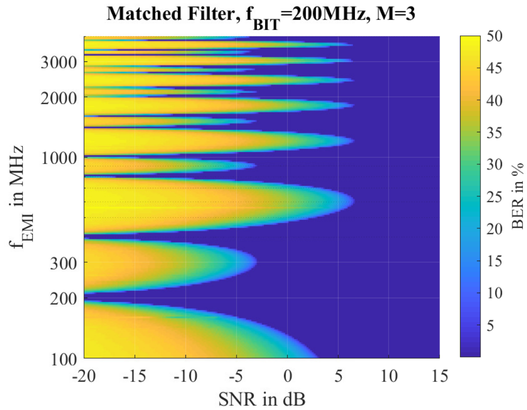
A. Baseline Without Oversampling

As a baseline, a set of 100 bits is disturbed multiple times by a CW disturbance. When using no oversampling, no matched filter or majority voting can be applied. The baseline is first investigated at f_{BIT} equal to $200\,\text{MHz}$ and at f_{EMI} equal to $500\,\text{MHz}$. Fig. 2 shows the reference situation for the BER in function of the SNR. Fig. 2 also shows that the baseline starts to have bit errors at an SNR equal to $6.532\,\text{dB}$. When using the inverse of (5), the amplitude of the disturbance is determined and shows that bit errors start to arise at $A_{\text{EMI}} = 1/3$ V. This value corresponds with the configured thresholds to detect a digital '1' or '0'. This BER in function of the SNR stays the same for any disturbance frequency, and is shown in Fig. 3, this due to the randomly distributed phase shift that is used in the simulation.

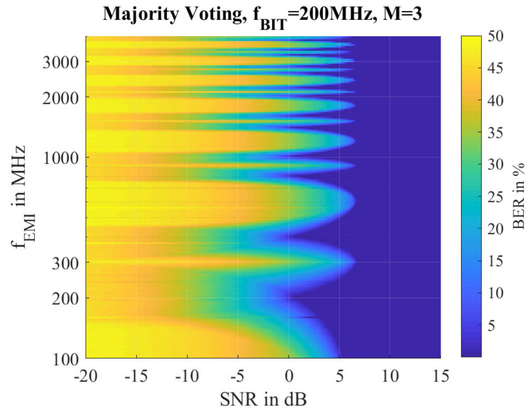
B. Simulation With Matched Filter and Majority Voter

Following up, the oversampling factor is increased and it turns out that it has a big influence on the BER as shown in Fig. 4 and 5. First, the effect of increasing the oversampling factor M to 3 and 5 is investigated in function of the EMI frequency. The first observation of Fig. 6 shows that certain EMI frequencies are more suppressed than others. The EMI frequencies that lay around integer multiples of the bit frequency have a lower BER than the baseline. Except for the integer multiples that are also a multiple of the oversampling factor. Comparing Fig. 6a with Fig. 6b and Fig. 6c with Fig. 6d shows that a matched filter is able to improve the BER even more than the majority voting technique and that the locations of improvement are similar.

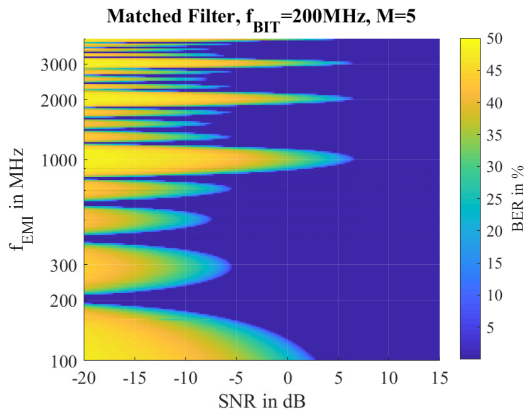
Next, the influence of the oversampling factor is compared. Fig. 7 shows that the BER in function of the SNR and the oversampling factor M for a bit frequency of $200\,\text{MHz}$ and an EMI frequency of $500\,\text{MHz}$. The effectiveness of the matched filter increases dramatically as the amount of samples per bit raises, up to a certain limit of M. The majority voting technique also shows improvement when increasing the



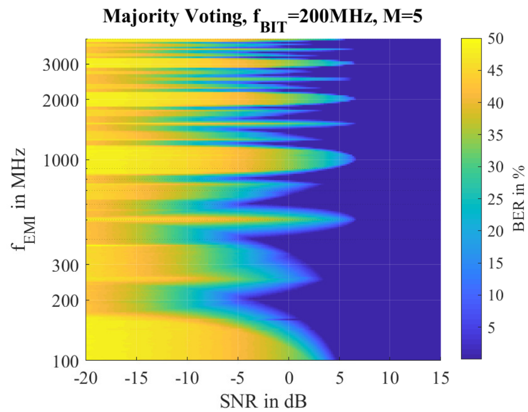
(a) Matched filter with three samplepoints.



(b) Majority voter with three samplepoints.



(c) Matched filter with five samplepoints.



(d) Majority voter with three samplepoints.

Fig. 6: BER in function of SNR and the EMI frequency f_{EMI} for a matched filter and majority voter with different oversampling factors.

oversampling factor, but not as dramatically as the matched filter. Fig. 7 also shows that using an even amount of samples and applying majority voting is always worse than using one less sample.

Finally, the filter and voting gain in function of the EMI frequency and the oversampling factor is shown in Fig. 8. This summarises the properties of both techniques. The results show that a filter gain up to $40\,\text{dB}$ is possible with a matched filter and the property of the integer multiples is clearly visible. Furthermore, the majority voting technique also shows improvements. Opposite to the matched filter, the majority voting technique shows no advances when f_{EMI} is 1/2 and 1/4 of the bit frequency.

VI. Conclusion

In this paper the performance of a matched filter and majority voting to cope with harsh CW EMI is investigated. The BER and the filter gain and voter gain at a certain BER was used as a metric to attest the performance of both techniques. The results show that both majority voting and a matched filter improve the BER of the communication system. This means that, if possible, at least one of those techniques should be used. When using a matched filter the BER decreases rapidly when increasing the oversampling factor and shows that adding even more sample points does not improve it any more. The majority voting results show that using an even amount of sampling points will always give a worse BER than using one less sample. Both of the techniques have the same property that their filter gain is maximised around the integer multiples of the bit frequency, except at integer multiples of the the sampling frequency. Although the majority voting system does not perform as well as the matched filter, it allows the user to have more information of how harsh the EM environment is at the receiver. It is up to the user to decide what technique fits best in its system.

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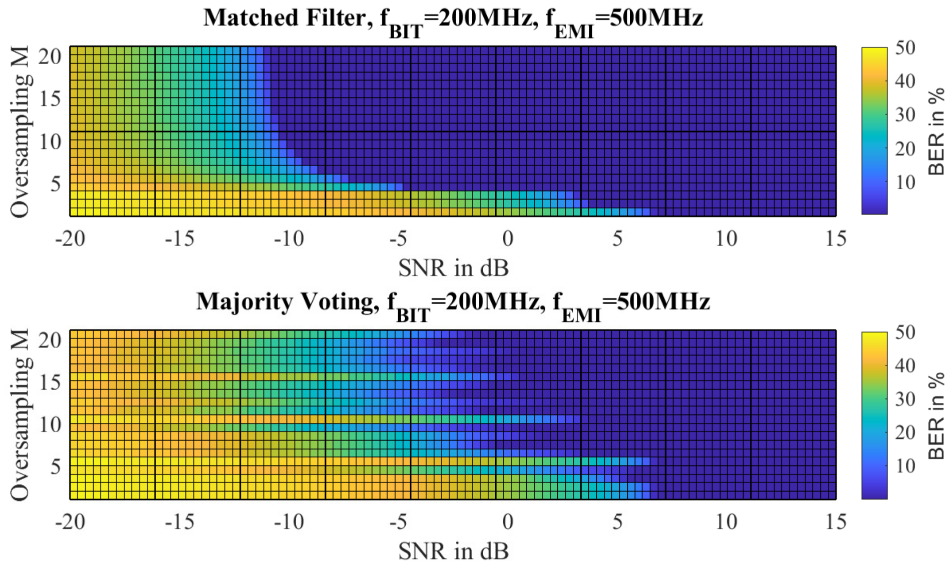

Fig. 7: BER in function of the amount of samples per bit at a bit frequency $f_{\text{BIT}} = 200$ MHz and an EMI frequency $f_{\text{EMI}} = 500$ MHz.

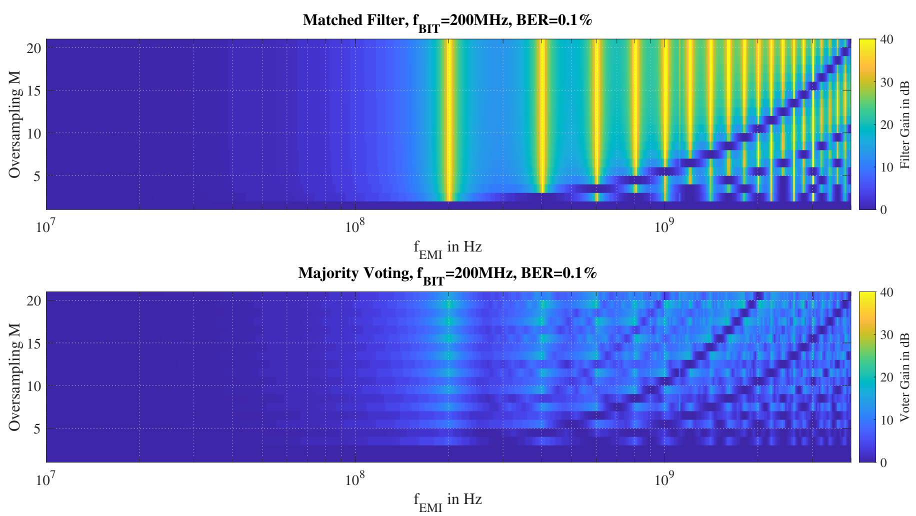

Fig. 8: Filter and voting gain in function of the amount of samples per bit at a bit frequency $f_{\text{BIT}} = 200$ MHz and an EMI frequency $f_{\text{EMI}} = 500$ MHz.

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