

# Multi-Notch Filter (MNF) Algorithm for Automotive Radio-Frequency (RF) Signal Processing and Applications

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## ABSTRACT

The radio frequency (RF) filter is a well-known technique that has been used in communication systems for a long time. It is able to limit the selected band from receiving signals or transmitting signals. The filter can be a low-pass filter, high-pass filter, band-pass filter, and notch-filter or combined filters. This paper presents the unique Multi-Notch Filter (MNF) which takes advantages of the properties of "sinusoid wave" and "linear functions". Since an automotive receiver is operated in noisy environments, this method is particularly useful to improve an automotive receiver's performance at the input stage when it immediately processes RF signals from an antenna. This type of filter can easily be implemented into an automotive receiver to notch out more unwanted frequency(s), such as harmonic frequencies, motor noise and very low frequencies (power line noise), which will result in better noise immunity for mobile receivers against noisy environments. In the following sections we will discuss; key criteria for good receiver design, the background theory of this unique multi-notch filter, the architecture of this multi-notch filter, and examples of this multi-notch filter's implementation for receiver.

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## KEY CRITERIA FOR A GOOD RECEIVER DESIGN

The fundamental requirements for a good receiver [1][2] must be the ability to receive very small signals (say  $<1\mu\text{V}$  for AM receiver) from remote broadcasting RF signals and to demodulate the what signal contains (this paper will not investigate high sensitivity receiver design). A good receiver also must be able to handle very strong wanted and unwanted signals. This can be particularly challenging when the receivers tunes to a desired weak signal, while the antenna also receives undesired strong signals from the nearby frequency spectrums. Figure-1 illustrates a standard 76cm rod car antenna that received whole AM band broadcasted signals which were detected by the receiver.

Figure-1 shows that two very strong signals, 750 KHz and 1000 KHz, both can cause serious de-sensitization and can create 2<sup>nd</sup> order and 3<sup>rd</sup> order intermodulation frequencies [1][2] in the AM band. Where 1250 KHz is the 3<sup>rd</sup> order intermodulation frequency from 750 KHz and 1000 KHz signals and 1500 KHz is the 2<sup>nd</sup> order harmonic of 750 KHz signal. In this case, it shows this receiver has poor performance on both 2<sup>nd</sup> order and 3<sup>rd</sup> order intermodulation. If a 750 KHz multi-notch filter was implemented in this receiver, its 2<sup>nd</sup> order harmonic and 3<sup>rd</sup> order intermodulation can be greatly improved. The above

phenomenon is not limited on AM receiver that can happen in any other radio-frequency communication system including cable communications system.

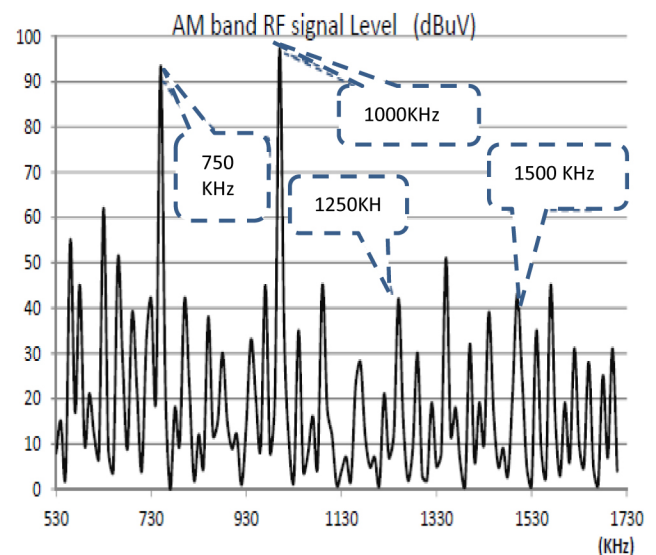


Figure-1. Radio detected RF signals across AM band

Furthermore, for example, the AM receiver's power line (50Hz or 60Hz) interference rejection is one of important criteria for a good AM receiver, because the car could be driven along a motorway with high voltage (say 33KV or higher) power lines running parallel. The car antenna and antenna cable can

induce high level signal of 50/60Hz and then feed all the noise into receiver. This 50/60Hz signal can overload the receiver which results in high noise and distortion at the top of the wanted signal with a 50/60Hz hum at speaker outputs. Many receivers have been implemented with some high-pass filters at the input stage. However, either due to high cost coils or due to high parts count, this 50/60Hz power line interference still presents in many AM receivers in the market. If multi-notch filter was implemented in the receiver, the car radios with power line noise rejection will be improved even more.

## THE BACKGROUND THEORY OF MULTI-NOTCH FILTER (MNF)

This paper will analyze the system in time and frequency domains, not in s-domain [7] or z-domain [8], since this MNF is constructed by time-delay manner. Additional studies can be found in the reference [3].

The multi-notch filter (MNF) is based on fundamental properties of “linear functions” and “sinusoidal wave”

All interference noise signals and broadcast radio frequencies (RF) signals are a linear sum function relationship. The broadcaster transmits signal(s) through space (could be air, cable, trees and buildings) and then the signal arrives at receiving antenna(s). When the transmitted signal propagates between broadcasting antenna and receiving antenna, there are many other unwanted signals and noise in the space as well. All those wanted and unwanted signals are a linear relationship to the receiving antenna. In another word, those signals only have “sum” or “subtraction” relationship without an inter multiplication relationship. When those combined signals arrive at the input stage of the receiver before they hit any nonlinear circuitry, the receiver should immediately filter out unwanted signals as much as possible.

Figure-2 shows the receiving antenna is not only picking up desired signal, it also receives many other interfering signals. The same example, the total signals energy ( $E_{\text{Total}}$ ) arriving at AM receiver input terminal is the **sum** of desired signal ( $E_d$ ), power-line ( $E_p$ ), Lightning ( $E_{L_n}$ ), electrical noises ( $E_N$ ) and other undesired broadcast signals ( $E_{ud}$ ).

$$E_{\text{Total}} = (E_d + E_p + E_{L_n} + E_N + E_{ud}) \cdot (\text{Antenna Efficiency})$$

Since the antenna sums all wanted signals and unwanted signals linearly, the combined signals can theoretically be decomposed into discrete frequency spectrums. With this property, the Multi-Notch Filter becomes one of the best receiver design skills to notch out the most harmful discrete frequencies.

Some well-known properties of trigonometric functions of sinusoidal wave will be implemented in this multi-notch filter design.

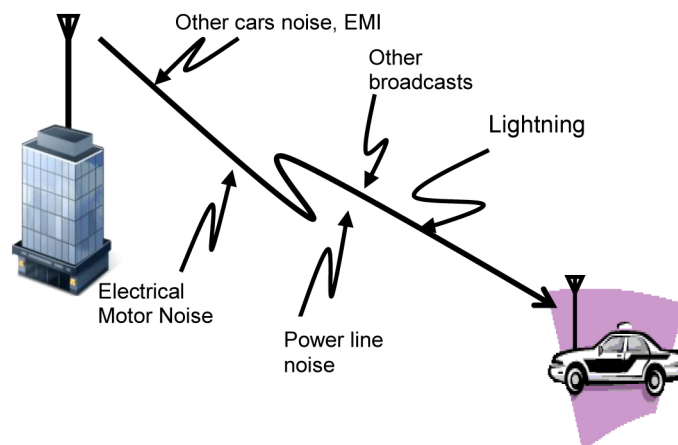


Figure-2. Indicate car antenna received broadcasting signal and many unwanted signals.

$\sin(A \pm n\pi)$  is still the same frequency of  $\sin(A)$  “sinusoidal wave”, but with some phases shifted. Where “n” can be any Real number.

$$\sin(A \pm \pi) = -\sin(A), \quad \sin(A \pm 2\pi) = \sin(A).$$

### Time-Shift Symmetrical Property

Upper half cycle of a pure sinusoidal wave should be identical to inverted lower half cycle with half cycle time shifted. Figure-3a and Figure-3b are periodic 300 KHz sinusoidal wave that illustrates this phenomenon.

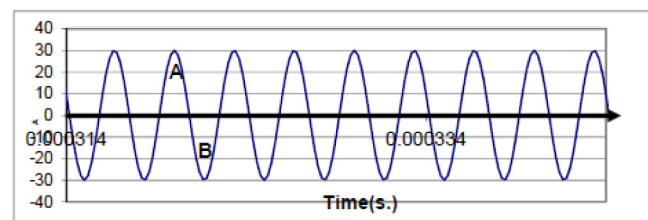


Figure-3a. 300KHz sin wave, marked point “A” and point “B”.

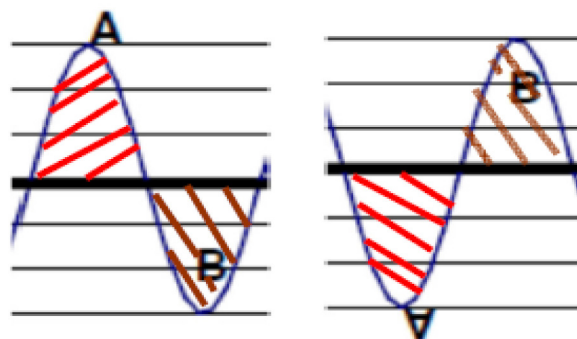


Figure-3b. Compare cycle (A, B) to inverted cycle (-A, -B) waveforms.

### Like-Hood Symmetrical (Near-Symmetrical) Property

The upper half cycle of a modulated RF signal is near-symmetrical to the adjacent lower half cycle if the frequency of modulation signal is much lower than the frequency of RF.

carrier. For example, a 300 KHz carrier is 95% modulated by a 1.5 KHz audio frequency (shown on Figure-4a). The ratio of 300 KHz and 1.5 KHz is 200 times. The higher this ratio, the more likely the upper half cycle is much more like-hood symmetry to the adjacent lower half cycle of the RF signal. Figure-4b and Figure-4c are the zoom-in wave forms of Figure-4a. In Figure-4c, the upper cycle at point "C" is 4.5780762V and the lower cycle at point "D" is 4.81467V. The difference is (error) 0.233908V which is very small compared to the 58 Volts maximum amplitude of AM RF signal. The error ratio is 0.00403 (1/247.9). Both upper half and lower half adjacent cycles are not exactly-symmetrical to each other, but they are acceptable for this like-hood symmetry to each other for the real world applications. If consider normal AM broadcast frequencies ranges of 522 KHz to 1710 KHz (North America) and typical 30% modulation. The error ratio can be three to five times lower than the error ratio in the above example. This concept is valid for many other types of modulation. The acceptable error rates for different types of modulation and for different broadcast frequencies are subjects for other studies.

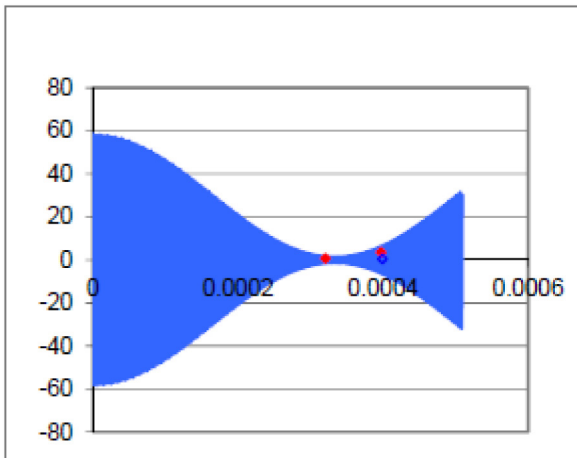


Figure-4a. AM modulation signal, time(s) vs. amplitude (V).

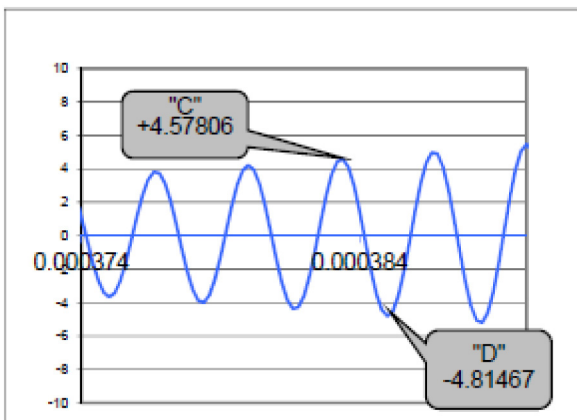


Figure-4b. Zoom-in waveform between 0.000374s and 0.000390s.

## TYPE-1 MULTI-NOTCH FILTER (MNF) ARCHITECTURE

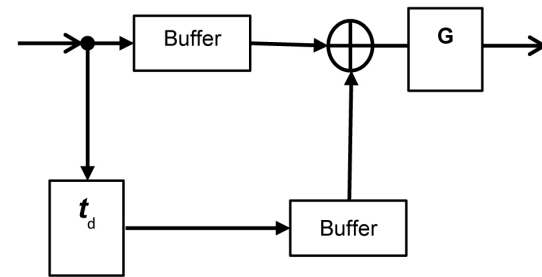


Figure-5. Type-1 MNF functional algorithm.

Figure-5 is one type of basic function block of MNF. This multi-notch filter is mainly constructed by a controllable "time-delay" function and a "sum" function. Taking Fig-3a's 300 KHz sinusoidal input signal as an example, delays the input signal by half cycle ( $\pi_3 = t_{d1} = 1.6667\mu\text{s}$ ) then sum it to the original input signal  $E_{in}$ . The result of the sum is zero, which means the 300 KHz is notched out. This can be expressed as:

$$\begin{aligned} E_{out} &= \sin(2\pi \cdot 300K \cdot t) + \sin(2\pi \cdot 300K \cdot t - \pi) \\ &= \sin(2\pi \cdot 300K \cdot t) - \sin(2\pi \cdot 300K \cdot t) \\ &= 0 \end{aligned}$$

Further investigation on the delayed time  $\pi_3 = 1.6667\mu\text{s}$  of 300KHz signal,  $\pi_3$  is 2 times of 600 KHz's half cycle,  $\pi_3$  is 3 times of 900 KHz's half cycle,  $\pi_3$  is 4 times of 1200 KHz's half cycle,  $\pi_3$  is 5 times of 1500 KHz's half cycle, ... and so on. The result of this multi-notch filter is able to eliminate all odd orders of harmonics of 300 KHz and double amplitude on all even orders ( $n=2, 4, 6 \dots$ ) of harmonics of 300 KHz. This feature can be expressed by the following Trigonometric functions.

Input signal "a(t)" has DC (0Hz), fundamental frequency and its 2<sup>nd</sup>, 3<sup>rd</sup>, 4<sup>th</sup>, 5<sup>th</sup>, ... n<sup>th</sup> order signals:

$$a(t) = \sum_{n=0}^{\infty} (\cos(2\pi n f t)) = 1 + \cos(2\pi f t) + \cos(2\pi 2 f t) + \cos(2\pi 3 f t) + \cos(2\pi 4 f t) + \cos(2\pi 5 f t) + \dots + \cos(2\pi n f t)$$

Delay a(t) by half cycle time of 1<sup>st</sup> order fundamental frequency  $\cos(2\pi f t)$ :

$$\begin{aligned} d(t) &= \sum_{n=0}^{\infty} (\cos(2\pi n f t - n\pi)) \\ &= 1 + \cos(2\pi f t - \pi) + \cos(2\pi 2 f t - 2\pi) + \cos(2\pi 3 f t - 3\pi) + \cos(2\pi 4 f t - 4\pi) \\ &\quad + \cos(2\pi 5 f t - 5\pi) + \dots + \cos(2\pi n f t - n\pi) \end{aligned}$$

$$\text{Let } A(t) = a(t) + d(t)$$

$$= 2 + 2\cos(2\pi 2 f t) + 2\cos(2\pi 4 f t) + 2\cos(2\pi 6 f t) + \dots + 2\cos(2\pi m f t)$$

where m is even number of n