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Hardware architecture for an anti-traffic noise system

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ABSTRACT

This work presents an energy efficient architecture for an anti-traffic noise system. The hardware is designed for a road side unit (RSU) in intelligent transportation systems. Fast Fourier Transform is the cornerstone for the suggested system. An ultra low power architecture for the FFT suitable for FPGA implementation is derived. Bit-widths for both data and twiddle factors are optimized for low-power. The architecture uses an efficient complex multiplier that has 25% less multiplications. An algorithm to compute the number of time-shared butterflies for a given FFT block size and a target throughput is elaborated. Finally synthesis results using fixed-point VHDL library and commercial IP are presented and compared with the proposed FFT processor.

1. Introduction

As a result of the expanding economical activities and the constant migration from rural to urban areas, road traffic has experienced an unprecedented growth. High volume of road traffic in cities can cause various anomalies such as air contamination, noise pollution, and road congestion. The relationship between noise levels and traffic volume has been investigated in [1].

Latest study has shown that noise pollution causes serious health problems such as hypertension, somatic health disorders, the release of stress hormones, and degradation in cognitive performance [2]. Fig. 1 shows the typical sources of noise in a modern city.

Traffic noise is caused primarily by vehicle engine and bad road/tyre interactions [3]. To combat noise pollution, the European Union (EU) has proposed a tight measure on the acceptable noise level emitted by vehicle engine and tyres [4]. A new label to identify the tyre parameters (rolling noise, wet grip, and energy efficiency) has been proposed by EU regulators [5]. The European regulation No. 661/2009 reports the maximum allowable rolling noise emitted by tyres. The regulation proposes three classes for tyres (C_1, C_2, and C_3). As an example, in the absence of snow, the maximum allowed rolling-noise for C_2 tyre is 72 dBA, whereas in traction mode, the limit is 73 dBA [6].

In the academic world, addressing the traffic noise has been the subject of intensive research in the various engineering branches (civil, electrical, and mechanical) [3,7,8]. However, no published reports have addressed the noise generated by tyres.

In [9], the authors have proposed a digital map to monitor the road noise. The measurements have been taken using a sound level meter of class 1. The authors have investigated the impact of the road porosity on the tyre noise. However, the work presents no counter-measure to combat traffic noise.

Sound level meter is an effective instrumentation to measure the acoustic pressure generated by a noisy source. Most sound levels meter are constructed using analog components (filter, amplifier, rms detector, and weighting network). Addressing tyre noise using sound level meter is impossible as its analog hardware cannot separate noise sources.

In [10], the author has presented a hardware oriented algorithm for the detection of tyre noise. The algorithm uses spectral techniques and a priory knowledge of the target noise. The advantages of FFT based spectrum analysis are reported in [11].

Our current work extends the analysis to account for the quantization noise, derives a low-power architecture for the FFT processor, and presents synthesis results using FPGA technology.

The remaining of this work is organized as follows. Section 2 reviews the proposed anti-noise system. Section 3 proposes an energy efficient architecture suitable for FPGA implementation. The experiments are then presented in Section 4. Finally the paper is concluded in Section 5.

2. Electronic system to combat traffic noise

In urban area, the traffic noise can be modeled as a sum of M uncorrelated noise sources, as shown in the following equation:

$$x(n) = \sum_{i=0}^{M-1} \zeta_i(n), \tag{1}$$

where ζ_i are uncorrelated discrete time stochastic process. Tyres can be a source of noise due to, for instance, bad driving behavior or bad interactions between road surface and tyre pitches.

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Fig. 1. Typical sources of noise in a modern city.

In [10], statistical analyses of the tyre noise have been reported. Then, an electronic system to combat drifting and traffic noise has been elaborated. The system uses a sound processing DSP, a Closed Circuit Television (CCTV) camera and a General Packet Radio (GPRS) transceiver. The core of the technique is the real-time spectrum analyses.

Sound processing hardware is the cornerstone of the system, where the noise is first captured using a micro-phone, then digitized, and finally processed in frequency domain for noise detection. The system sample rate is 44.1 Ksamples/s. The algorithm for the proposed system is shown in Fig. 1. The efficiency of the system is reported in [10]. The complexity of the algorithm is $N\log(N)$, where N is the transform size for the FFT algorithm.

Algorithm 1. Algorithm to combat drifting and traffic noise presented in [10].

Inputs: frequency vector (f_i), tolerable amplitude (A_i), sampling frequency (F_s), size of the FFT window (N_{FFT}).
Output: vehicle license's plate(s_v) and GPS coordinate.
Sample the input signal at F_s and store $N_{samples}$ in the input buffer (Buf_I). {The sample size should be power of two}
$i = 0$
detect ← **false**
while $i \le \log_2(N_{samples})$ **do**
$x \leftarrow Buf_I(i : i + N_{FFT} - 1)$ {Read a data window of size N_{FFT}}
$X_F \leftarrow FFT(x)$ {Transform the time domain window into frequency domain using an FFT algorithm.}
In the frequencies f_i compare the amplitude of X_F with tolerable amplitude A_i
if $|X_F(f_i)| \ge A_i$ **then**
detect ← **true**
end if
$i \leftarrow i + N_{FFT}$ {Point to the next coming N_{FFT} samples}
end while
if detect is **true**
return GPS coordinates and vehicle's license plate.
end if

The system can be implemented on a road side unit (RSU). The algorithm is initialized with a set of input frequencies that correspond to the amplitude of tyre noises. These frequencies can be determined analytically or experimentally.

In this work, frequencies at which the tyre noise occurs have been experimentally determined. Each frequency bin has maximum allowable noise amplitude stocked in the vector A_i. The last two input parameters to the algorithms are the size of the FFT algorithm and the sampling frequency. The transform size depends on the sampling frequency as demonstrated in [10]. The algorithm outputs the license plate of the violating vehicle and the GPS location of the road-side unit. The FFT algorithm is the core of the anti-traffic noise system, where the sampled sound data is fed continuously to the FFT processor. Noise levels above maximum allowed threshold are detected by considering sound data spectrum. The detector compares the amplitude at each frequency bin (f_i) to the threshold value (A_i).

3. VLSI architecture of anti traffic noise

3.1. FFT processor

Discrete Fourier Transform (DFT) of the given N_{FFT}-point sampled sound data is given by the following equation:

$$X(k) = \sum_{n=0}^{N_{FFT}-1} x(n) e^{-knj\frac{2\pi}{N_{FFT}}}, \quad \forall k \in [0, \ldots, N_{FFT}-1]. \tag{2}$$

The FFT algorithm is a fast technique to implement the DFT. The idea behind the fast algorithm is to generate a recursive algorithm that takes advantage of the properties of the twiddle factor, $W_N = e^{-j(2\pi/N_{FFT})}$. The recursion to compute DFT is based on the following equation [12]:

$$X(p,q) = \sum_{l=0}^{L-1} \left[W_N^{lq} W_L^{lp} \sum_{m=0}^{M-1} x(m,l) W_M^{mq} \right], \tag{3}$$

VLSI implementation of the FFT algorithm is accomplished using time shared Radix-R processing element. Most proposed FFT architectures in the academic and industry works use Radix-2, Radix-4, Radix-8, or mixed radix mode. Higher radix mode is attractive for high speed FFT. Comparison between the aforementioned radices is presented in [12] and [15].