

Enhancing Sound Quality in Bluetooth Audio Systems Using Kalman Filtering

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ABSTRACT

Bluetooth communication systems are constrained to use a low cost filtering technology, which requires designers to implement inexpensive noise reduction techniques. Improving Bluetooth sound and audio quality has been a topic of research over the years. Sound and audio quality in vehicles are areas that still require improvements in order to achieve better customer experience when using Bluetooth communication systems.

This paper proposes a low cost, simple, and effective method to reduce noise in Bluetooth systems using Kalman Filtering. Our novel method is proposed to be used in vehicular Bluetooth applications. We have created a MATLAB/SIMULINK model to validate the proposed method. Results have demonstrated significant noise reduction and improvement to the processed speech signals.

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INTRODUCTION

Bluetooth is a short range wireless communication that operates in the Industrial Scientific and Medical (ISM) band at 2.4 to 2.485 GHz [1]. Bluetooth is used widely in many applications. Most North America vehicles are equipped with Bluetooth capability, in which drivers can use Bluetooth connections to pair their phones with the vehicles' audio system and establish hands free calls utilizing the vehicles' audio system. Bluetooth was designed to be used in low cost and low power applications. Due to the hands-free, low cost and low power consumption design criteria, Bluetooth was a natural fit for the automotive industry. In 1999, the Bluetooth Special Interest Group (SIG) group formed a Car Working Group, which created all the specifications to introduce Bluetooth into vehicles [2]. The Hands-Free profile was the first of the specifications to be created by this group, which identified all the protocols establishing connections between the users' mobile phones and the vehicles' audio systems. In The Basic Data Rate (BDR), the rate of Bluetooth can reach 1 Mbps when Gaussian Frequency Shift Keying (GFSK) is used. However, the rate can be increased to 2 Mbps when Differential Quadrature Phase Shift Keying (DQPSK) is used and 3 Mbps when Differential Phase Shift Keying (8DPSK) is used. These data rate manipulations are called the Enhanced Data Rate (EDR).

Enhancing speech signals through noise reduction has been researched in many literatures. Several techniques have been proposed. The success of reducing and suppressing noise in speech samples has contributed to enhancements in voice and audio related applications, such as telephone conversations, voice recognition as well as voice communication using Bluetooth systems [3]. A fast multi-channel colored noise reduction algorithm was proposed to remove colored noise from speech signal [4]. The presence of

background noise degrades the quality of the speech signal; therefore, making it difficult to understand the speaker. The effect of background noise on speech signals has been analyzed and several authors have proposed the use of the Kalman Filter (KF) for noise reduction. KF is an efficient recursive filter that estimates the internal state of a linear dynamic system from corrupted measurements. Researchers have claimed their methods of using Kalman Filtering proved to produce better results in comparison to the spectral subtraction and Wiener Filter methods. With all the proposed techniques and methods, in which some of them were effective, degradation and poor quality of speech signals still pose a problem. More enhancement methods are being researched to improve the quality of speech signals [5], [6].

In 1960, Rudolf E. Kalman presented the concept of his Kalman Filter [7]. KF is an estimator, in which it estimates the status in linear dynamic systems by minimizing the Minimum Mean Squared Error (MMSE). It is originated from Bayes' probabilistic theory, in which if a number of past samples are known, the future samples can be predicted and updated based on the continuously collected measurements [8]. KF is one of the best known statistical estimators in linear systems in Gaussian noise environment; however, other versions of KF have been developed to handle nonlinear and non-Gaussian noise, such as Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF).

Kalman Filtering has been proposed in digital communication receivers to estimate and optimize modulation techniques in the receivers. A new method was proposed to enhance the performance of GFSK and DQPSK using an Interactive Kalman Filtering (IKF) technique, in which a multiple Kalman filters work together to optimize the received signals [9]. A third order model was proposed

in an attempt to find a solution to the problem of demodulation and improve performance of a frequency modulated speech signal using an Extended Kalman Filtering [10].

In this paper, we are proposing a novel method to implement two coupled Kalman Filters that work jointly to reduce noise in the speech signal samples. To our knowledge, the integration of Kalman Filtering technique in the Bluetooth transmitter to suppress background noise from speech signals has not been proposed in previous literatures. Also, an EKF will be utilized to estimate the phase of non-coherently modulated GFSK and DQPSK in the Bluetooth receiver. This paper is organized as follows. The first section presents an introduction of the topic and lists some of the research that has been completed. [Section 2](#) describes the theory behind the Kalman Filtering and provides details of our proposed methods. [Section 3](#) presents the simulation and results in validating the proposed method. The last section includes the conclusion and future works related to this research.

KALMAN FILTERING FOR SPEECH SIGNAL ENHANCEMENTS IN BLUETOOTH SYSTEMS

Different methods are used to model speech signals. One of the most common methods is called Autoregressive (AR), which can be done by taking a relatively small segment of the speech and predict the next speech signal using prior samples. It is assumed that the speech signal is stationary and its coefficients do not change during these short segments. Let $S_{k/K-1}$ be a speech signal at sample k that can be predicted recursively using the past speech samples up to $k - 1$. Using the AR model with p th order, the speech signal can be modeled as [10]:

$$S_{k|k-1} = -\sum_{i=1}^p a_i S_{k-i} + w_k \quad (1)$$

where a_i are the prediction coefficients; w_k is the so called driving process, which is assumed to be a zero-mean noise with variance σ_w^2 ; and p is the order.

In-Vehicle Noise Characteristics

Bluetooth voice quality in the vehicle poses a concern that needs to be addressed. There are many different noise types that may affect Bluetooth sound quality in the vehicles' audio system. Ideally, the voice or sound quality of the hands free calls should be the same quality as talking in private mode (mobile phone). There are many noise types in the vehicle that degrade voice quality. A study of different noise types that exist in vehicles has shown that some of the most critical noise sources are described as follows:

- Distortion or static noise can be heard on both far-end side and in-vehicle side. This noise is caused by many factors, such as reception of the cellular network, interference with other electronic devices inside the vehicle (i.e. power inverter), driving around high power electrical lines and cellular towers.

- Vehicle background noise is common and can be caused by several factors, such as HVAC fan noise, engine noise, wind noise, sunroof/window noise, raining noise, turn signal indicator noise, road noise such as pot holes, speed bumps, etc. These noise types are the main focus of this research.
- Wi-Fi interference noise often interferes with the Bluetooth's frequency and causes static noise or feedback overlapping. Having a Wi-Fi device enabled inside a vehicle can decrease the Bluetooth sound quality. In general, any kind of radio frequency at the same channel as Bluetooth will cause some noise interference.

Dual Estimations Using Kalman Filtering

The dual estimations concept has been explored in several studies with different applications. In previous literature, authors proposed to take advantage of so-called instrumental variable techniques to estimate both the received signal and the associated parameters [11]. They proposed using two conditionally linked linear Kalman Filters to avoid using an EKF to estimate both states and coefficients. The first KF uses a new observation to estimate the incoming signal, while the second KF uses this estimated signal to estimate the AR coefficients.

The Dual Estimation method will be utilized in this research to process the speech signal sample to predict the next speech signal $S_{k/k-1}$ based on the past measured received signals $S_{k-1}, S_{k-2}, \dots, S_{k-p}$. This is called joint estimation since both the signal S_k and the coefficients a_i need to be estimated. The estimated values depend on each other. Two KFs are proposed in order to perform the estimation, which allows the analysis to be run linearly and avoid using any nonlinear approximation methods. KF1 estimates the speech samples, while KF2 estimates the coefficients. [Figure 1](#) shows a layout of this proposed method [9].

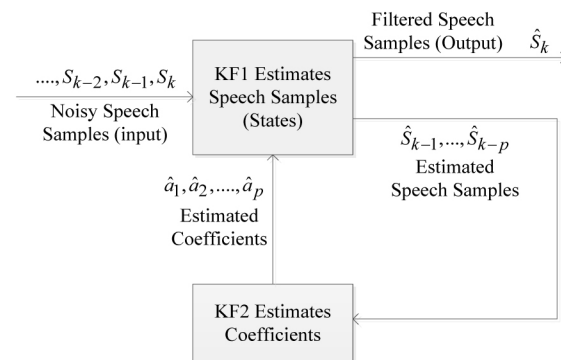


Figure 1. Dual Estimations Using Two Kalman Filters

Estimation of the Speech Samples

Let $\mathbf{S}_k = [S_k \ S_{k-1} \ \dots \ S_{k-p+1}]^T$. In order to use Kalman Filtering, [equation \(1\)](#) needs be put in the following state space format [11]:

$$\mathbf{S}_k = \Phi_k \mathbf{S}_{k-1} + \mathbf{g} w_k \quad (2)$$