Analog Transmission of Vocoder Features

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Given a vector of vocoder features $\mathbf{f}$, use an autoencoder E to map them to a dimension d latent vector $\mathbf{z}$ where d is even. The magnitude of each element of $\mathbf{z}$ is constrained to a maximum of 1, but unlike digital modulation is continuusly valued and not constrained to a discrete set of points. For bandwidth efficient transmission over the channel the elements of $\mathbf{z}$ are mapped to $d/2$ complex symbols $\mathbf{q}$. Compared to classical digital modulation, the elements of $\mathbf{z}$ can be considered BPSK symbols (continuously valued, analog bits), and the elements of $\mathbf{q}$ analog QPSK symbols.

Our goal is to determine if reasonable speech quality can be obtained over a channel of bandwidth $B < 3000$ Hz and SNR between 0 and 6dB, both comparable to Single Side Band (SSB) - a common power and bandwidth efficient form of analog radio communication.

1 Noise Simulation

The autoencoder output $\mathbf{z}$ is updated every $T_z = 1/R_z$ seconds, giving a BPSK symbol rate of:

$$R_b = d/T_z \tag{1}$$

For example with $T_z = 0.04, d = 80, R_b = 2000$ symbols/s. The QPSK symbol rate is given by:

$$R_q = \frac{d}{2T_z} \tag{2}$$

For example with $T_z = 0.04, d = 80, R_q = 1000$ symbols/s

We wish to simulate a channel of known E_b/N_0, where E_b is the energy of each BPSK symbol, and N_0 is the noise power per unit bandwidth. The energy of each BPSK symbol E_b is the symbol power S divided by the symbol rate $R_b = 1/T_b$. The noise per unit bandwidth is the total noise power N divided by the bandwidth B of the system. If we are simulating at one sample per symbol,

$B = R_b$:

$$\begin{aligned} \frac{E_b}{N_0} &= \frac{S/R_b}{N/R_b} \\ &= \frac{S}{N} \\ &= \frac{A^2}{\sigma^2} \end{aligned} \tag{3}$$

where A is the amplitude of each BPSK symbol and $\sigma^2 = N$ is the variance (mean noise energy per sample). If the noise is zero mean, we can estimate σ^2 over K noise sample r_i:

$$\sigma^2 = \frac{1}{K} \sum_{i=0}^{K-1} r_i^2 \tag{4}$$

We generate noise samples r_i by sampling a unit variance, zero mean Gaussian noise source $\mathcal{N}_i(0,1)$ that is scaled by σ:

$$\begin{aligned} r_i &= \sigma \mathcal{N}_i(0,1) \\ \sigma &= \frac{A}{\sqrt{Eb/N_0}} \end{aligned} \tag{5}$$

In practice we add noise to the QPSK symbols. Due to orthogonality, this can be viewed as two independant channels that have the same noise power:

$$r_i = \sigma \mathcal{N}_{2i}(0,1) + j\sigma \mathcal{N}_{2i+1}(0,1) \tag{6}$$

2 SNR Measurement

It is useful to formulate expressions for estimating SNR from the BPSK and QPSK symbols. The Signal to Noise ratio (SNR) is given by:

$$\begin{aligned} \frac{S}{N} &= \frac{E_b R_b}{N_0 B} \\ &= \frac{E_q R_q}{N_0 B} \end{aligned} \tag{7}$$

At one sample per symbol, the power, the mean energy of each QPSK symbol over a window of K samples is given by:

$$E_q = Var(q_i) = \frac{1}{K} \sum_{i=0}^{K-1} |q_i|^2 \tag{8}$$

As each QPSK contains 2 BPSK symbols, then energy is split evenly:

$$E_b = E_q/2 = Var(q_i)/2 \tag{9}$$

For example if the symbol amplitude is $A = 1, E_b = A^2 = 1$, then $E_q = 1+1 = 2$.

For transmission over multipath channels we arrange the QPSK symbols as N_c parallel carriers, each running at a symbol rate of R_s symbols/s, where R_s is chosen based on delay spread considerations and is typically around 50 Hz. However the OFDM carriers are arranged such that the total QPSK symbol rate over the channel R_q remains constant, so for a given carrier power S, $E_q = S/R_q$ remains constant. The expressions above can be used as a check for the noise injection process:

1. Set a target E_b/N_0 for the simulation run.
2. Establish the target SNR from (7) evaluated using the target E_b/N_0.
3. Measure $Eq = Var(q_i)$ over a sample of transmitted symbols.
4. Calculate measured SNR using (7) and compare.

3 Glossary

Symbol	Explanation	Units
B	noise or signal bandwidth	Hz
d	dimension of latent vector bfz	
E_b/N_0	energy per BPSK symbol on spectral noise density	
E_q/N_0	energy per QPSK symbol on spectral noise density	
N_c	Number of carriers	
$\mathbf{q}$	vector of QPSK symbols	
q_i	single QPSK symbol, element of $\mathbf{q}$	
R_b	BPSK symbol rate	symbols/second
R_q	QPSK symbol rate	symbols/second
R_s	per carrier QPSK symbol rate	symbols/second
R_z	latent vector update rate	Hz
T_b	BPSK symbol period	seconds
T_q	QPSK symbol period	seconds
T_s	per carrier QPSK symbol period	seconds
T_z	time between latent vector updates	seconds
SNR	signal to noise Ratio	
S	signal power	Watts
N	noise power	Watts
$\mathbf{z}$	Autoencoder output latent vector	
z_i	single latent vector element of $\mathbf{z}$, a BPSK symbol	

Table 1: Glossary of Symbols