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System Models for the Detection of Wireless Microphone Signals in Noisy Environment for Cochlear external devices

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ABSTRACT

In our earlier two research papers we have proposed two'UART to WIFI modules' namely IEEE 802.15.4 and BLE 4.0 wireless architectures to establish wireless Communication Among Speech Processor and Transmitter 0f most recent cochlear Implant Naida CI Q90.The two proposed architectures are wireless communication systems which are much prone to adjacent noises hence quality of the voice gets degraded for the CI users.The signal to noise ratio (SNR) is one of the important measures for reducing the noise. Hence we have derived an mathematical expression in the energy detector model which is used to find the detection probability. This theoretical expression is evaluated under various values of P_{fa} and derived an expression to compute the predetermined threshold. The simulation shows the detection performance of energy detection over non fading AWGN channel in the noisy environment and results for great improvement in the detection performance with increase in SNR. We find good performance of the energy detector even at low SNR. Simulation results closely match with theoretical results. The proposed mathematical analysis in the model can be incorporated to sense the signal from the microphone in wireless CIs and shall be used in a clinical validation in a quiet environment.

Keywords : CI, SNR, ROC, AWGN, NRI Response, mapping.

I. INTRODUCTION

In recent research, we proposed two wireless architectures[4,5] for wireless communication among external devices (Speech Processor and Transmitter(Head Piece)) of Cochlear Implants[1] as shown in the figure(1),to overcome some of the practical problems and are described in [4,5]. The architectures are based on the Bluetooth Low Energy BLE 4.0 [5] and other based on IEEE 802.15.4 [4] as shown in the block diagram (fig 2). The Architectures use the 'UART to BLE 4.0 module' and are available in local market. The Idea is to configure the Voice processing system and the Head piece (Transmitter) as IEEE 802.15.4 and BLE 4.0 hot spot. Then the proposed modules will connect Voice processing hotspot for communication with Head Piece (Transmitter).

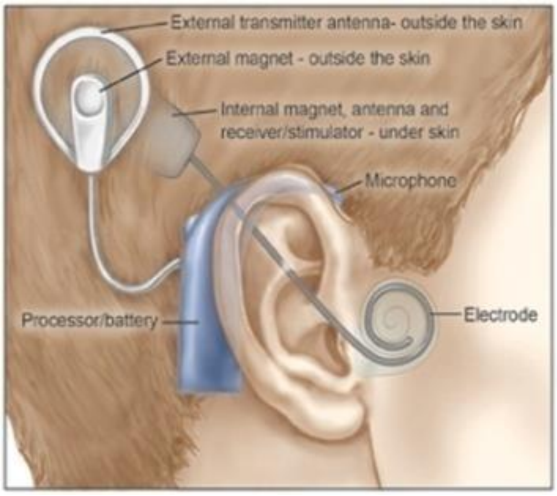
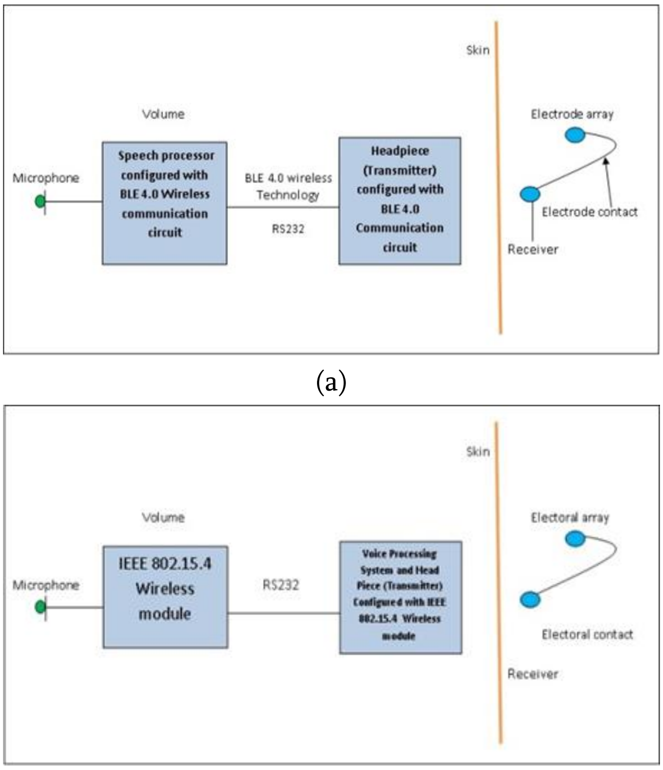


Figure 1. External devices of CI

1.1 Thought Process

The proposal is to develop the system for managing wireless communication among external devices i.e Speech Processor and Head Piece (Transmitter) of CI [1]. The system includes first device including a Bluetooth Low Energy (BLE) and IEEE 802.15.4 wireless communication circuit configured to receive and transmit data using both wireless communication technology. The second device including a wireless testers configured to wirelessly communicate with the first device and test the both wireless communication circuit according to a wireless test mode in response to a test command associated with the wireless test mode, the second device including an analysis initiator coupled wireless testers configured to generate the test command in response to a signal requesting a diagnostic analysis of an environment of the wireless communication according to a wireless test mode in response to a test command associated with the wireless test mode, the second device including an analysis initiator coupled to the Low power BLE tester and configured to generate the test command in response to a signal requesting a diagnostic analysis of an environment of the wireless communication, wherein at least one of the first device and the second device includes the Speech Processor and Head Piece (Transmitter) of CI as shown in fig (2).



(a)

(b)

Figure 2 . (a) Proposed Bluetooth Low Power BLE 4.0 wireless module configured for CIs External Devices. (b) Proposed architecture for CIs External Device communication configured with IEEE 802.15.4

Since the above said Architectures IEEE 802.15.4 and BLE 4.0 are wireless modules, The speech will get degraded by additive background noise and is actively being done by the use of microphone array , spectrum subtraction , etc. Imperfection can be seen in the method of the noise reduction using two microphones which can be considered as a directional microphone with a blind spot in the arrival bearing the noise. When many noise sources exist, an increase in number of microphones cannot be avoided. The adjacent noise may dominate the signal strength and suppresses the SNR leading to degradation of quality of voice. Hence to remove such noises in the received signals and improve the SNR we have developed the mathematical models. The mathematical models are described in section 2.0.

II. System Models for the Detection of Wireless Microphone Signals in Noisy Environment

In the above said Wireless modules i.e IEEE 802.15 and BLE 4.0, External devices (Head Piece and Speech Processor) of CI are communicating wirelessly. The adjacent noise may dominate the signal strength and suppresses the of SNR leading degradation of quality voice. Hence to remove such noises in the received signals and improve the SNR we have developed the mathematical models.
Models are illustrated shown as below.

Let $y(t) = s(t) + w(t)$ be the received signal, where $s(t)$ is the possible transmitted wireless microphone signal and $w(t)$ is additive white Gaussian noise (AWGN) with zero mean and variance ${\sigma_n}^2$. The $y(t)$ is sampled with period T_s , resulting in $y(n) = y(nT_s)$. There are two hypothesis: H_0 , signal does not exist; and H_1 , signal exist. The received signals samples under the two hypothesis are therefore, respectively, as follows [13]

$$y(n) = \begin{cases} w(n) & :H_0 \\ s(n) + w(n) & :H_1 \end{cases}$$
(1)

Let us consider $N \approx 6 \times 10^4$ number of samples of the received sampled signal. Two probabilities are of interest. The conditional detection probability P_d defines at hypothesis H_1, $P_d[H_1 / y(n) = s(n) + w(n)]$, the probability of sensing algorithm having detected the presence of the signal; and the conditional false alarm probability P_{fa} which defines at hypothesis H_0 , $P_{fa}[H_1 / y(n) = w(n)]$, the probability of sensing algorithm claiming the presence of the signal. Under H_1 , we define the signal to noise ratio (ρ) at the receiver as $\rho = \frac{{\sigma_s}^2}{{\sigma_n}^2}$.

2.1 Energy Detector Model

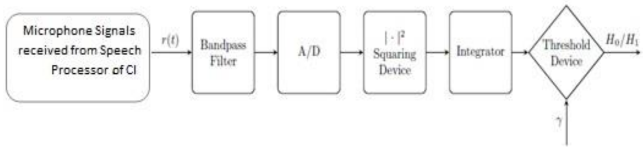


Figure 3. Energy Detector Model

In the model of energy detector the noise and adjacent signals are removed through filtering signal $y(t)$ with required bandwidth B [15]. Using analog to digital (A/D) converter the signal filtered through Bandpass filter is sampled and quantized. The energy of the received signal is computed through square-law device and an integrator. The integrator output represents the decision statistic Y . The presence of transmitted signal under the hypothesis H_1 or absence under H_0 is determined by comparing the Y with a predetermined threshold. The presence or absence of a transmitted signal can be modelled as binary hypotheses problem as originally proposed by [6], [7] and latter followed by most researchers [8, 9]. The received signal samples under two hypotheses are defined in equation (1).The energy detector is defined as

$$Y = \sum_{n=1}^{N} |y(n)|^2 \qquad (2)$$

The distribution of the decision variable Y will be central chi-square X_N^2 under H_0 and non central chi-square $\tilde{X}_N^2$ with N degrees of freedom under H_1 . The distribution can be expressed as [14]

$$Y \sim \begin{cases} X_N^2 & :H_0 \\ \tilde{X}_N^2 & :H_1 \end{cases} \qquad (3)$$

Its probability density function can be written as

$$f_Y(y) = \begin{cases} \dfrac{1}{\sigma_n^N \, 2^N \, \Gamma\left(\frac{N}{2}\right)} y^{\left(\frac{N}{2}\right)-1} \exp\left(\dfrac{-y}{2\sigma_n^2}\right) & :H_0 \\ \dfrac{1}{2\sigma_n^2}\left(\dfrac{y}{\varsigma}\right)^{\frac{N-2}{4}} \exp\left(\dfrac{-1}{2\sigma_n^2}(\varsigma + y)\right) I_{\frac{N}{2}-1}\left(\dfrac{\sqrt{\varsigma y}}{\sigma_n^2}\right) & :H_1 \end{cases}$$
(4)

Where the non centrality parameter $\varsigma = \sum_{i=1}^{N} \mu_i$ and μ_i is the mean of the i^{th} Gaussian random variable of test Y. $I_M(.)$ is the M^{th} modified Bessel function of the first kind and $\Gamma(.)$ is the gamma function $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt$. The test statistic Y is compared with a predetermined threshold γ, to decide on one of the two hypotheses H_0 and H_1. The probability of detection (P_d) and probability of false alarm (P_{fa}) can be computed as

$$P_{fa} = P(Y > \gamma | H_0) = \int_\gamma^\infty f_Y(y) \quad dy \qquad (5)$$

$$P_d = P(Y > \gamma | H_1) = \int_\gamma^\infty f_Y(y) \quad dy \qquad (6)$$

Threshold γ can be evaluated by inserting (4) in (5)

$$P_{fa} = \int_\gamma^\infty \frac{1}{\sigma_n^N 2^N \Gamma\left(\frac{N}{2}\right)} y^{\left(\frac{N}{2}\right)-1} \exp\left(\frac{-y}{2\sigma_n^2}\right) \quad dy \qquad (7)$$

Substituting $t = \frac{y}{\sigma_n^2}$ in (7) and further integrating the P_{fa} results in

$$P_{fa} = \int_{\gamma/\sigma_n^2}^\infty \frac{t^{\frac{N}{2}-1}}{2^{\frac{N}{2}} \Gamma\left(\frac{N}{2}\right)} \exp\left(\frac{-t}{2}\right) \quad dt \qquad (8)$$

To derive the probability of detection the probability density function defined under H_1 in (4) is inserted in (6). By substituting $t = \frac{y}{\sigma_n^2}$ and using definition of ρ the probability of detection is given by

$$P_d = \int_{\gamma/\sigma_n^2}^\infty \frac{1}{2}\left(\frac{t}{\rho}\right)^{\frac{N-2}{4}} \exp\left(\frac{-(t+\rho)}{2}\right) I_{\frac{N}{2}-1}\left(\sqrt{t\rho}\right) \quad dt \qquad (9)$$

Substituting $t = x^2$, $\rho = a^2$ and with further simplification, the P_d can be written as

$$P_d = \frac{1}{a^{\frac{N}{2}-1}} \int_{\sqrt{\gamma/\sigma_n^2}}^\infty x^{\frac{N}{2}} \exp\left(\frac{-(x^2+a^2)}{2}\right) I_{\frac{N}{2}-1}(ax) \quad dx \qquad (10)$$

We can rewrite the equation (10) using the definition of generalized Marcum–Q function [20, 1.2] as

$$P_d = Q_{\frac{N}{2}}\left(\sqrt{\rho}, \quad \sqrt{\frac{\gamma}{\sigma_n^2}}\right) \qquad (11)$$

Since, the precise computation of Marcum–Q function is quite difficult, it is represented in the new form as [11,12]

$$P_d = 1 - \sum_{n\geq 0} (-1)^n \exp\left(\frac{-\rho}{2}\right) \frac{L_n^{\frac{N}{2}-1}\left(\frac{\rho}{2}\right)}{\Gamma\left(\frac{N}{2}+n+1\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}+1} \qquad (12)$$

Where $L_n^k(x)$ is the generalized Laguerre polynomial of degree n and order k. The absolute convergence of the series in (12) can be easily shown [16] as

$$\left| \sum_{n\geq 0} (-1)^n \exp\left(\frac{-\rho}{2}\right) \frac{L_n^{\frac{N}{2}-1}\left(\frac{\rho}{2}\right)}{\Gamma\left(\frac{N}{2}+n+1\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}+1} \right|$$

$$\leq \exp\left(\frac{-\rho}{2}\right) \sum_{n\geq 0} \frac{1}{\Gamma\left(\frac{N}{2}+n+1\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}+n} \left| L_n^{\frac{N}{2}-1}\left(\frac{\rho}{2}\right) \right|$$

$$\leq \exp\left(\frac{-\rho}{2}\right) \sum_{n\geq 0} \frac{1}{\Gamma\left(\frac{N}{2}+n+1\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}+n} \frac{\Gamma\left(\frac{N}{2}+n\right)}{n!\,\Gamma\left(\frac{N}{2}\right)} \exp\left(\frac{\rho}{4}\right)$$

$$\leq \exp\left(\frac{-\rho}{4}\right) \frac{1}{\Gamma\left(\frac{N}{2}\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}-1} \sum_{n\geq 0} \frac{\left(\gamma/2\sigma_n^2\right)^{n+1}}{(n+1)!}$$

$$= \exp\left(\frac{-\rho}{4}\right) \frac{1}{\Gamma\left(\frac{N}{2}\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}-1} \left(\exp\left(\frac{\gamma}{2\sigma_n^2}\right) - 1\right) \qquad (13)$$

Inserting (13) in (12) the P_d for AWGN Channel is

$$P_d = 1 - \exp\left(\frac{-\rho}{4}\right) \frac{1}{\Gamma\left(\frac{N}{2}\right)} \left(\frac{\gamma}{2\sigma_n^2}\right)^{\frac{N}{2}-1} \left(\exp\left(\frac{\gamma}{2\sigma_n^2}\right) - 1\right) \qquad (14)$$

III. Simulation Results

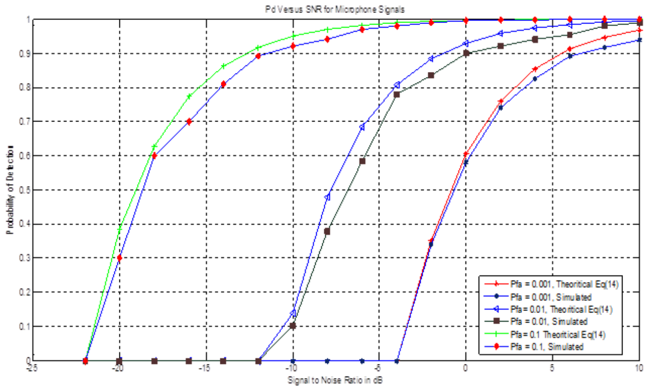


Figure 4. Pds versus SNR for microphone Signals

In the simulation, we have collected the signals from the microphone of Q70 and Q90 processors from Advanced Bionics. We have used complementary receiver operating characteristics (ROC) curves $(P_{md} \text{ versus } SNR)$ to show the detection performance of energy detection over non fading AWGN channel in the noisy environment. From the figure, we notice that there is a great improvement in the detection performance with increase in SNR. We find good performance of the energy detector even at low SNR. Simulation results closely match with theoretical results. The results are shown in figure 4.

3.1 NRI Response

We also argue that the above mathematical model when included in Advanced Bionics Sound wave software for mapping of Naida Q90 processor from advanced bionics for a severe to profound CI Implanted patient will get the NRI Response [1] by Electrode arrays as shown in the table 1. Which are the NRI Responses from the current architecture of Q90 processor.

Table 1. NRI response from electrode array

Electrode array no's	Stimulation range in Clinical Units CU	NRI response in micro volts Low to High
3	140 – 260	119 - 533
7	100 – 220	32 - 315
11	180 – 300	74 - 440
15	180 – 300	85 - 366
16	100 – 220	27 - 135

Similarly we also expect various environments responses of the mathematical model when included in the Sound Wave Software, are recorded as shown in the table 2.

Table 2. Environment response by Naida Q70 and Q90 processor

Sl No	Environments	Response in percentage
1	Speech in Quiet	46%
2	Music	21%
3	Speech in Noise	28%
4	Noise	5%

IV. Conclusion and Future work

The derived expression (14) in the energy detector model can be used to find the detection probability. This theoretical expression is evaluated under various values of P_{fa}. Equation (8) can be used to compute the predetermined threshold. To the best of our knowledge, the proposed mathematical analysis in the model can be incorporated to sense the signal from the microphone for the above said wireless modules such as IEEE 802.15.4 and BLE 4.0 for Cochlear Implants which may help us in replacing the wired media. In our upcoming research we are presenting a single circuit design that embeds all the external device of CI in to single IC.

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