IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 13, Issue 5, Ver. I (Sep.-Oct. 2018), PP 03-12
www.iosrjournals.org

Intrusive Assessment of Speech Quality over Wireless Networks

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Abstract: *This work examined the intrusive aspect of objective assessment of the quality of speech transmitted over wireless mobile networks using the automated end-to-end PESQ algorithm. The immense merits objective assessment techniques have were highlighted. The raw PESQ scores were mapped using the more accurate Morfitt and Cotanis U. S. Patented logistic function. Correlating the mapped PESQ MOS scores with the subjective MOS score, coefficients of 0.77, 0.81, and 0.75 were obtained for speeches transmitted over three different wireless networks respectively.*

Keywords: *Speech quality, assessment, MOS, intrusive, PESQ, mapping function, correlation.*

Date of Submission: 18-08-2018 Date of acceptance: 03-09-2018

I. Introduction

Quality of service (QoS) of telecommunication services and applications was defined by (1) as: “The collective effect of service performance that determines the degree of satisfaction of a user of the service.” Voice services provided on telecommunication networks is the major type of service in highest demand for network resources. Quality of voice services therefore, which refers to the clearness of a speaker’s speech that makes for its intelligibility, as perceived by a listener, takes center stage in ensuring provision of quality services by network operators. This becomes particularly important to be credibly estimated in order to determine the reliability, viability and overall health of telecommunication networks whether fixed, fixed wireless or mobile wireless.

Estimation of the quality of transmitted speeches other than by parametric approach which is based on network parameters obtained from measurements by meters and indicators at the operation and maintenance center (OMC) and other nodes in the network (2), can also be by perceptual approach. (3) examined some aspects of these two perspectives for the 3G UMTS network.

The perceptual approach to assessing speech quality is built upon the perspectives of users of services provided by the network. This as expressed in the quality framework of International Telecommunication Union (ITU-T) (4) is the level of quality of the services received or experienced by users of the service as perceived by them. This perceptual quality of service is either subjective or objective. Figure 1 shows a schematic diagram of techniques involved in perceptual speech quality assessment, namely:

1. Subjective Assessment: degraded (or output) speech is listened to by human subjects who make their ratings based on internationally accredited standards. The perceived quality of such speech is determined upon the background of the cognitive senses of what normal (clean) speech should sound like.
2. Objective Assessment: this is the application of computational models to mimic human auditory perception of speech to predict quality of transmitted speech, and is of the following two types:

(i) Intrusive Approach: predict speech quality by making use of both the original and the degraded speeches in its computations;
(ii) Non-intrusive Approach: compute and predict speech quality only from the psychoacoustic features of degraded (output) speech comparing it with a reference model.

The unit of expressing estimated speech quality is the mean opinion score (MOS), which was first used in 1996 for voice codec (5). It is a well-established parameter which has over the years been applied to both analogue and digital telephone connections and telecommunications devices such as codec, for characterizing the quality of telephony equipment and services (6,7).

Subjective speech quality testing was developed to provide an overall end-to-end score of the quality of a system or network from users’ perceptive perspective, irrespective of the type of network technology or design in operation (1, 8). But it is non-technical and only based on the perceptual judgment by listeners or receivers of the transmitted speech of such degradation factors as background noise, distortion level and overall acceptability (9).

Objective speech quality assessment techniques on the other hand have the following general characteristics (1, 10):

1. They offer automatic voice quality assessment on communication systems;
2. They are based on complex mathematical models;
3. They utilize algorithms that compute a mean opinion score (MOS) value using a small portion of the speech in question;
4. They can be coded and computerized;
5. They are widely used to supplement subjective test results;
6. They are less costly means of implementing signals quality assessment;
7. They can be used to continuously measure speech quality on real-time basis on live telecommunication networks or voice processing systems.

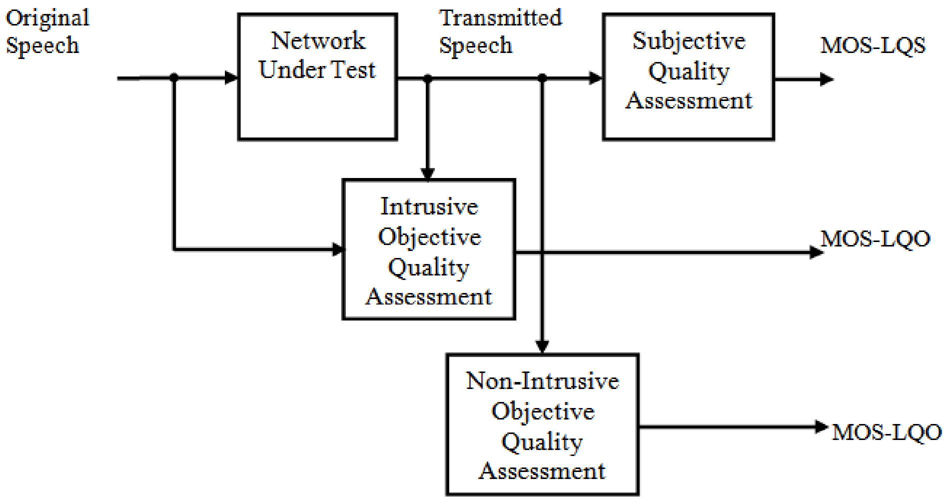


Figure 1: Perceptual Speech Quality Assessment Approaches.

II. Objective Approach To Speech Quality Assessment

Objective methods of assessing speech quality make use of mathematical models to automatically estimate the perceived quality of speech signals without dependence on human subjects at such a level that would equal or be close to that obtained from human subjects in subjective assessment. These methods predict speech quality based on speech signals that are physically measurable and are classified into Parameter-based, Signal-based and Packet-layer models.

The parametric models mostly make use of estimates of network properties to predict quality of speech communication and usually carried out during network planning before implementation for full characterization of the network (9,12,13).Signal-based models make use of the degraded signals from an existing telecommunication networks or speech processing systems in evaluating the quality of the transmitted speech. (12) noted that several signal-based methods focus on models of speech production or speech signal likelihood, while others exploit aspects of perception such as noise loudness. Objective signal-based models are either intrusive or non-intrusive in nature.

Though they are computationally very intensive, objective quality measures are used for monitoring speech quality on telecommunication networks based on end-user's experience, in order to optimize the networks and speech processing systems for better quality, increased capacity or cost effectiveness (12).

III. Intrusive Objective Speech Quality Assessment

The Intrusive models, also known as double-ended or input-output-based models, receive both the original speech and the degraded or transmitted speech as input into the model. It was noted in (12) that many intrusive models have been developed since 1980 for estimating speech quality. These models extract key auditory features or properties through a process of perceptual transform from an original or "clean" speech known as the reference speech and from its processed or degraded version obtained from a transmission network. Intrusive models mimic the human auditory system, wherein speech signals are transformed into auditory nerve excitations through psychoacoustic processes which include bark scale frequency warping and spectral power to subjective loudness conversion through the use of different psychoacoustic models (14). The features of the original and degraded speeches are compared, and the amount of their deviation is used to compute an estimated mean opinion scores (MOS), from which the level of quality of the degraded speech with reference to the original speech is determined.

Perceptual models form the core of intrusive techniques for assessing speech quality. The earlier ones include the Masked-error model, which was proposed by Schroeder in 1979 and extended by Brandenburg in 1987 (13, 15). Simple masking methods according to (13) were used to obtain the mean noise to masking ratio (NMR) in order to estimate the audibility of coding noise in a speech coder such that the difference on the time frame between reference and distorted speeches was counted to be noise. The waveform-comparison algorithm models namely the signal-to-noise ratio (SNR) and the segmented signal-to-noise ratio (SSNR) techniques (16, 17) required low computational algorithms but they do not correlate well with subjective assessment results at the face of comparison of diverse distortions (10).

The SNR waveform-comparison technique does not sufficiently provide a prediction of speech quality in modern telecommunication networks, which led to the development of some more complex objective quality assessment measures (18). Some of these were discussed in (9,19), and they include the Cepstral Distance (CD) which compares two smoothed spectra in the cepstral domain, Log Spectral Distance (SD) which obtains the log difference of the power spectra of the clean and the degraded speech signals, the Weighted Spectral Slope (WSS) based on weighted differences between the spectral slopes of 36 overlapping frequency bands, and the Auditory Spectrum Distance (ASD) which compares the audible time (in ms), pitch (in Bark) and amplitude (in dB) representations of the clean and the degraded speech signals.

Perceptual-domain models require that psychoacoustic processes are utilized to transform both the reference and degraded speech signals in accordance with the peripheral auditory system. (15) indicated that this transformation follows the psychoacoustic model for loudness calculation developed by Zwicker and Fastl. In estimating speech quality, the integral quality is obtained from the combination of the perceptual transform and a simulation of the cognitive processes in the human auditory cortex. Perceptual-domain models include the Bark Spectral Distortion (BSD) whose perceptual transformation emulates auditory phenomena of critical integration in the cochlea and the loudness compression, and the distortion obtained as the square of the Euclidean distance between the transformed speeches. The Modified Bark Spectral Distortion (MBSD) incorporated a noise-masking threshold so as to make a difference between audible and inaudible distortions. Perceptual Speech Quality Measure (PSQM) developed in 1994 and published as an ITU-T standard in (18) compares a coded signal to a source signal by mimicking sound perception and judgement processes of humans. PSQM is one of the four most important intrusive objective model, with the others being Perceptual Analysis Measurement System (PAMS), Perceptual Evaluation Speech Quality (PESQ), and Perceptual Objective Listening Quality Analysis (POLQA) discussed below (20).

Other perceptual-domain models include Measuring Normalization Blocks (MNB), which was developed by (16,21) and based primarily on essential components of objective estimators of perceived speech quality namely: perceptual transformation and distance measures reflecting the magnitude of the perceived distance between two perceptually transformed signals. The Perceptual Analysis Measurement System (PAMS) describes audible errors introduced by the system or network as the differences between the original and the degraded speeches and obtained the total errors from the error spread.

IV. Perceptual Evaluation Of Speech Quality (PESQ)

The Perceptual Evaluation of Speech Quality (PESQ) was developed and deployed for automated end-to-end assessment of the quality of transmitted speech on telephone networks (22), and was standardized in (23). It is a more robust speech quality measurement model which incorporates some properties from its predecessors like the perceptual transformation of the PSQM99 model and the time-alignment algorithm of the PAMS model. The wideband version of PESQ (WB-PESQ) which was developed in 2005 (15) was standardized as (24), and it is currently the most widely used perceptual model particularly for wideband audio systems with frequency range of 50–7,000 Hz(25). The most recent Perceptual Objective Listening Quality Analysis (POLQA) is aimed at correcting alignment defects in PESQ model and at predicting integral speech transmission quality for all types of telecommunication networks when it is fully in use.

On the other hand, the perceptual evaluation of audio quality (PEAQ) algorithm designed and standardized as (26), also makes it possible to evaluate the quality of stereo signals (27). PESQ is being extensively adopted in carrying out series of voice quality assessments on virtually all telecommunication networks. It is also being used on voice-on IP (VoIP) networks and for predicting speech quality in modern codecs (28).

The PESQ algorithm is widely used by manufacturers, vendors and operators of telecommunication equipment and networks for speech quality testing. The PESQ algorithm has been deployed in applications like the development of new speech coding algorithms, and for exploring quality effects of variations of bit rate, input levels, and channel errors of speech codecs. It has also been deployed in equipment selection for comparing the quality effects of distortion scenarios on communication systems and technologies, and in equipment and network monitoring and optimization (29). It is a “full reference” algorithm in that it requires the reference speech signal in estimating the quality of the degraded speech signal. It offers high accuracy and repeatability particularly in dedicated tests of speech quality in live telecommunication networks, like in drive tests on mobile networks.

In the structure of PESQ model shown in figure 2 (12, 30), the reference and degraded speech signals are level-aligned to the same power level, filtered (FFT), time-aligned, equalized, and processed through auditory transformation. Input speech signals are broken into phonemes each of 32ms duration from which spectral characteristics are calculated and perceptual differences from the reference signal are obtained for each phoneme (31). These are the distortion parameters which are extracted, aggregated and mapped to the subjective MOS.

The auditory transform in PESQ algorithm maps the processed signals in time-frequency resolution in accordance with loudness perception to represent the human auditory system. This includes using an FFT with a Hamming window to calculate the instantaneous power spectrum in each frame known as Bark spectrum, calculating the mean Bark spectrum for the active speech frames in order to obtain a ratio between reference and degraded spectra which is useful for equalization of the reference to the degraded speech signals at ± 20dB, determining gain variations in the reference and the degraded, and mapping the Bark spectrum to loudness to obtain the perceived loudness in each time – frequency representation.

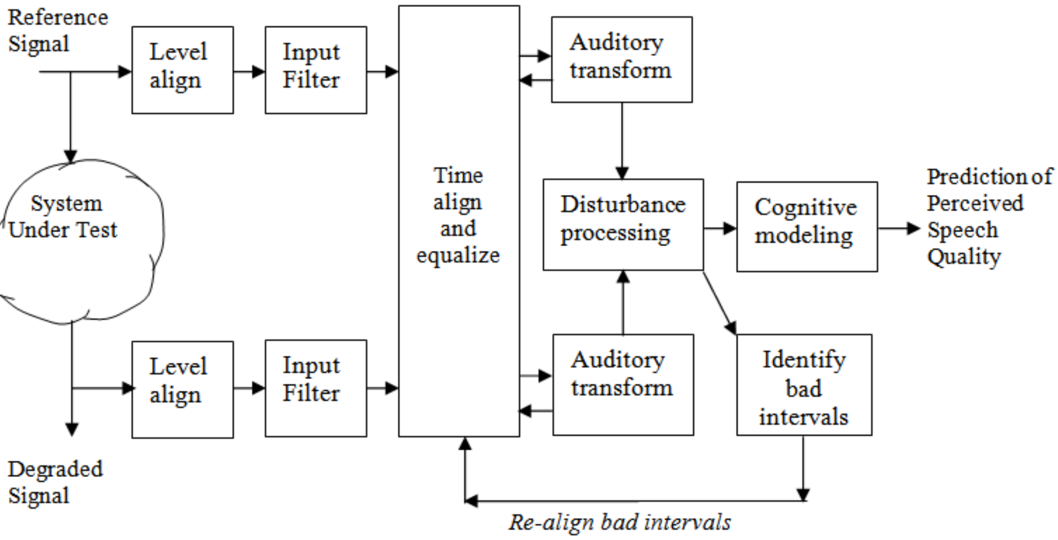


Figure 2: Structure of the PESQ model (12).

The values of differences in disturbance inherent in the reference and degraded speech signals are aggregated to obtain a non-linear average using (32):

$$L_p = \left[\frac{1}{N}\sum_{m=1}^{N} \text{disturbance}\ (m)^p\right]^{1/p} \qquad (1)$$

In order to compute the difference existing between the reference and the degraded speech signals, these speeches are broken into phonemes of about 32ms which are overlapped by 50% and 20 phonemes are aggregated into a long 320ms syllable.

A measure of perceived disturbance is estimated for each phoneme by calculating the symmetric and asymmetric disturbances D_{sn} and D_{an} and the aggregation of phoneme disturbance D_{sn} and D_{an} for every syllable, L_{DS} and L_{DC} are given by (33):

$$L_{DS} = \left(\frac{1}{20}\sum_{i=1}^{20} D_{sn}^{6}\right)^{1/6} \qquad (2)$$

and,

$$L_{DC} = \left(\frac{1}{20} \sum_{i=1}^{20} D_{an}^{6} \right)^{1/6} \quad (3)$$

The aggregated symmetric and asymmetric syllable disturbances are obtained by mean square algorithm and given by:

$$d_{sym} = \left(\frac{1}{N} \sum_{i=1}^{N} L_{DS}^{2}\,(i) \right)^{1/2} \quad (4)$$

and,

$$d_{asym} = \left(\frac{1}{N} \sum_{i=1}^{N} L_{DC}^{2}\,(i) \right)^{1/2} \quad (5)$$

where, N is the number of syllables in PESQ measurement window T.

The speech quality prediction is made from the two disturbance parameters, given above, and given by (32, 33):

$$PESQ_{MOS} = 4.5 - 0.1\, d_{SYM} - 0.0309\, d_{ASYM} \quad (6)$$

Goldstein and Rix (30) extended PESQ to measure terminals in mobile and hands-free telephones using the ITU-T P.AAM (acoustic assessment model). They found out that AAM has higher correlation with subjective MOS than with PESQ.

V. Pre-Processes To The Objective Quality Assessment

Reference or original speech samples used as raw materials for speech quality assessment are obtained from various speech databases. Instead of purchasing foreign-based speech databases or corpuses like the ITU-T P-series Suppl.23, NOIZEUS-960, NOIZEUS-2240, and E4 (34), we decided to locally build a speech database based on internationally standardized provisions and techniques outlined in (35). This was done to ensure issues of accent and intonation does not cause problem for subjects when listening to transmitted speeches in order to make their ratings during subjective quality tests.

The speeches were recorded with professional sound recording systems – complete Focusrite Scarlett Sound Studio Pack with advanced CUBASE LE software, a multi-track digital audio workstation (DAW) capable of taking multi source input, loaded on a Pentium Quad Core computer system. Recording was carried out in a professional studio with background noise level being less than the ideal 30dB prescribed by ITU-T.

Speech samples were recording from eight (8) males and eight (8) females with 4 speeches recorded from each person, bringing the recorded speeches to a total of 64 original speeches. The recorded speech is then converted from '.amr'speech format to the '.wav' speech format for processing.

The 64 wav speech samples were transmitted over a couple of mobile wireless networks. Three set of transmissions were carried out: two intra-networks (E to E network and G to G network) and one inter-network (E to M network), bringing the total transmitted speeches to 192. These transmitted speeches were made available for the speech quality tests that were carried out.

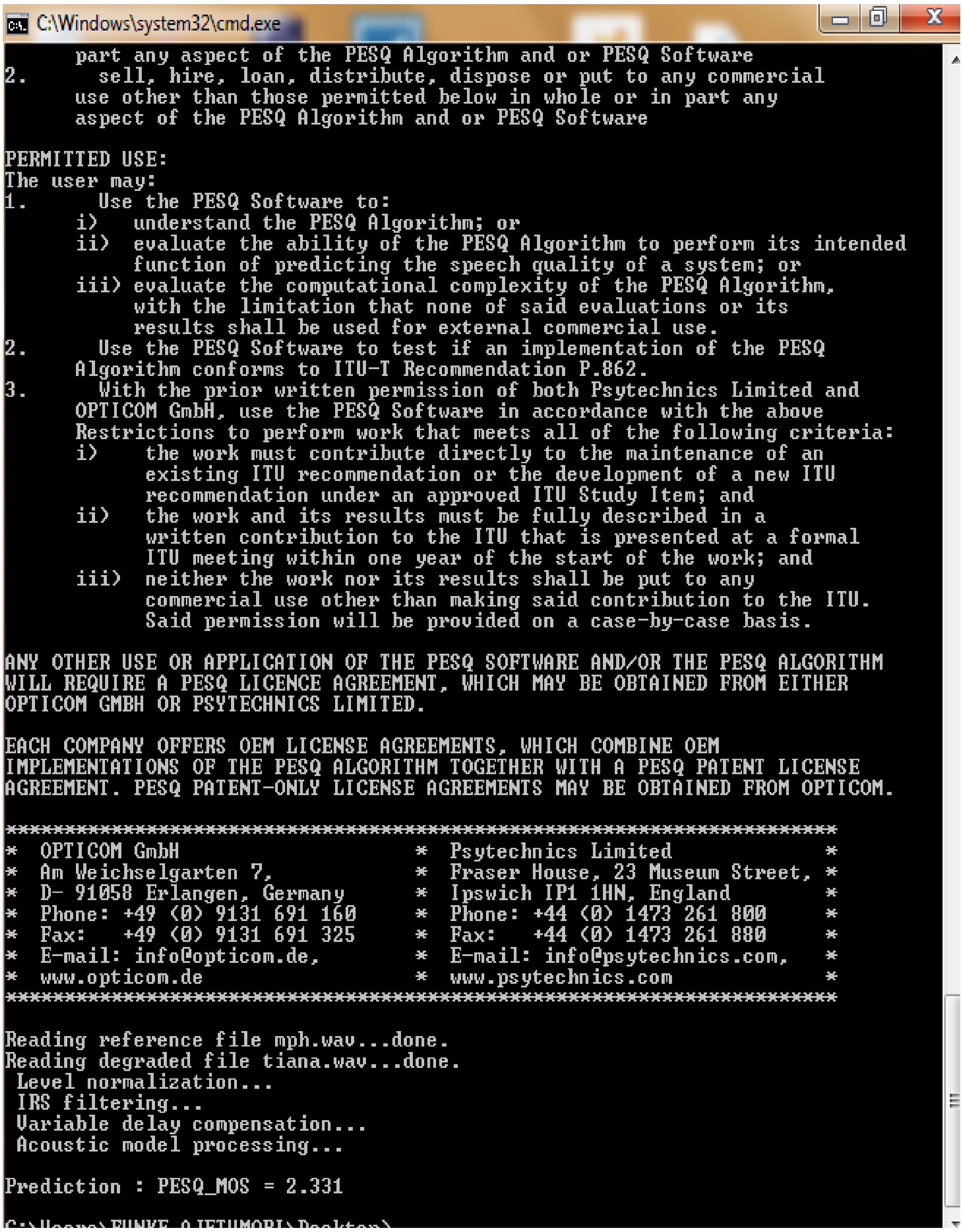
Subjective quality test was carried out for all speeches transmitted through the chosen networks using the listening-only test approach. The ratings done by subjects were based on the absolute category rating (ACR) scale of 1 to 5, where 1 stands for bad quality and 5 for excellent quality. The results of the of the subjective rating were collated per transmitted speech, summed up and averaged over the total number of subjects. The values obtained were known as the mean opinion score (MOS) and were recorded per speech.

VI. Implementing The Objective Quality Assessment

The Perceptual evaluation of speech quality (PESQ) as a robust first level objective (intrusive) model for end-to-end speech quality assessment of narrowband telephone networks and speech codecs was deployed for this work based on the provisions of ITU-T P.862. PESQ Testing was conducted using the ITU-T PESQ Source Code written in C++ software.

ITU-T PESQ Source Code

The latest version of the PESQ code, version 2.1, was obtained from the ITU-T website http://www.itu.int/rec/T-REC-P.862-200511-I!Amd2/en and compiled using a C++ Compiler. The compressed package was downloaded and uncompressed using: # unzip T-REC-P.862-200102-I!!SOFT-ZST-E.zip. Compiling the C-code using Dev C^{++} and run the PESQ file, simulated PESQ program was accessed using Command prompt (cmd) launched as a black terminal window shown in figure 3.



```
C:\Windows\system32\cmd.exe
      part any aspect of the PESQ Algorithm and or PESQ Software
2.      sell, hire, loan, distribute, dispose or put to any commercial
      use other than those permitted below in whole or in part any
      aspect of the PESQ Algorithm and or PESQ Software

PERMITTED USE:
The user may:
1.      Use the PESQ Software to:
      i)   understand the PESQ Algorithm; or
      ii)  evaluate the ability of the PESQ Algorithm to perform its intended
           function of predicting the speech quality of a system; or
      iii) evaluate the computational complexity of the PESQ Algorithm,
           with the limitation that none of said evaluations or its
           results shall be used for external commercial use.
2.      Use the PESQ Software to test if an implementation of the PESQ
      Algorithm conforms to ITU-T Recommendation P.862.
3.      With the prior written permission of both Psytechnics Limited and
      OPTICOM GmbH, use the PESQ Software in accordance with the above
      Restrictions to perform work that meets all of the following criteria:
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            written contribution to the ITU that is presented at a formal
            ITU meeting within one year of the start of the work; and
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***********************************************************************

Reading reference file mph.wav...done.
Reading degraded file tiana.wav...done.
 Level normalization...
 IRS filtering...
 Variable delay compensation...
 Acoustic model processing...

Prediction : PESQ_MOS = 2.331
```

Figure 3: Command prompt showing PESQ result

In C++, a project file is created and saved in a special folder. The PESQ file is compiled and saved under project. The PESQ file was then executed and PESQ quality score obtained for tabulation.

Files of original speech, degraded speech and simulated PESQ program are saved in a folder on the desktop, which are accessed for each speech file (having .wav extension added to the filename and the sampling rate used which is +8000). This step is repeated for all the speeches inputting the original speech and the corresponding degraded speech to give PESQ MOS score.

PESQ Mapping Function

The PESQ MOS results obtained for each speech category, that is, an original speech and the corresponding degraded speech, for the three sets of network transmissions carried out were tabulated and the data were analysed. The internal mapping polynomial function in the PESQ algorithm only result in the raw scores obtained from implementing the algorithm to occupy an output range of -0.5 to 4.5. This is different from the normal Subjective MOS rating obtained from ACR tests occupying the range of 1 (for bad quality) to 5 (for

excellent quality).Before the raw PESQ quality score can be correlated with the Subjective MOS score, it has to be mapped to a new scale that can be linearly approximated to the Subjective MOS scale.
Mapping is carried out with the use of a transfer function for better correlation, which helps to correct the mismatch in the quality score range. Many mapping functions have evolved over time at correcting this mismatch, like the Auryst mapping function among others (36). The following are among the major mapping functions available in literature for speech signals (narrowband):

1. ITU-T Rec. P.862.1 Amendment to PESQ (37):

$$y = 0.999 + \frac{4.999 - 0.999}{1 + e^{(-1.4945x + 4.6607)}} \tag{7}$$

2. United States Patented logistic function by Morfitt and Cotanis (30):

$$y = 1 + \frac{4}{1 + e^{(-1.7244x + 5.0187)}} \tag{8}$$

where x is the raw PESQ Score and y becomes the mapped PESQ MOS score (MOS-LQO).

In making comparative analysis of these two mapping functions, table 1 compares the minimum quality score and the maximum quality score of the raw PESQ score, the de-facto Subjective MOS score, and the mapped PESQ MOS score.

It could be seen from this comparative analysis that the Mapped PESQ MOS Score due to the United States Patented logistic function has accuracy of 93.7% to the Subjective MOS and the P.862.1 mapping function has accuracy of 86.8% to the Subjective MOS.

With the usage of a mapping function the capability of the PESQ algorithm to provide better accuracy is being increased. Therefore, there is the need to choose the mapping function with better accuracy. To this end, the logistic (mapping) function patented for Morfitt and Cotanis showed better accuracy than that standardized in ITU-T amendment to the PESQ ITU-T Rec. P.862 published as ITU-T Rec. P.862.1. The Morfitt and Cotanis logistic (mapping) function was therefore used for analysis in this work.

Table 1: Comparative analysis of mapping functions in (36) and (37).

	Raw PESQ Score	Subjective MOS Score	U. S. Patented logistic function Mapped PESQ MOS Score	ITI-T Rec. P.862.1 Mapped PESQ MOS Score
1.	-0.5	1	1.01113798	1.01684331
2.	4.5	5	4.75763496	4.54863832
Difference between highest & lowest scores		4	3.74649697	3.47131660
%age of MOS Score		100%	93.7% of MOS	86.8% of MOS

The quality of each of the transmitted speeches is determined from the values of the mapped PESQ Listening Quality Only (MOS-LQO) rather than from just the PESQ raw quality scores only.

VI. Scatter Plots And Correlations Analysis

Correlation analysis is of the essence of fitting the intrusive quality assessment to the subjective quality score to determine its figure of merits, with normalized correlation given by $\rho \in (0, 1)$(38). This is because subjective quality assessment is been adjudged the best and most accurate technique for quality assessment despite its challenges and constraints.

Correlation plots of the quality scores obtained from subjective tests (MOS) and the intrusive objective tests were made with the aid of scatter plots on MATLAB software. These are shown in figures 3 to 5, each including a plot of the line of regression.

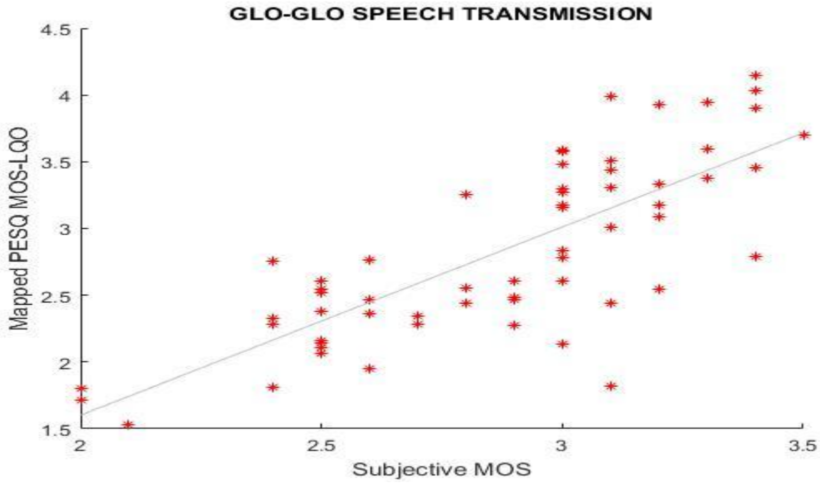

Figure 3: Scatter/regression plots (GLO-GLO).

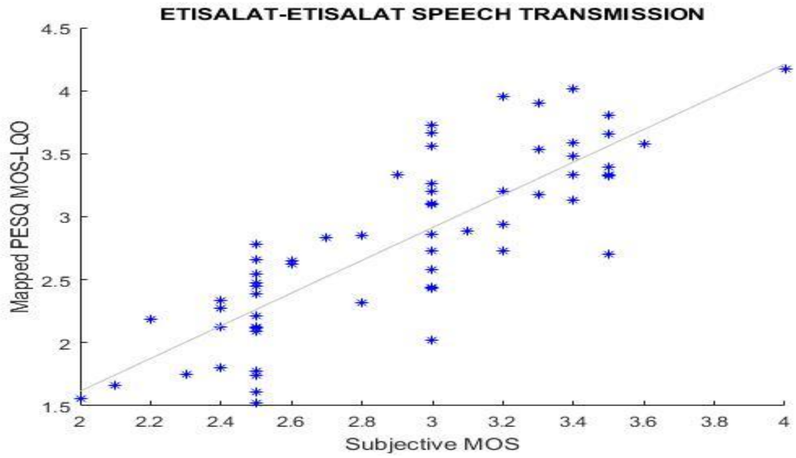

Figure 4: Scatter/regression plots (ETI-ETI)

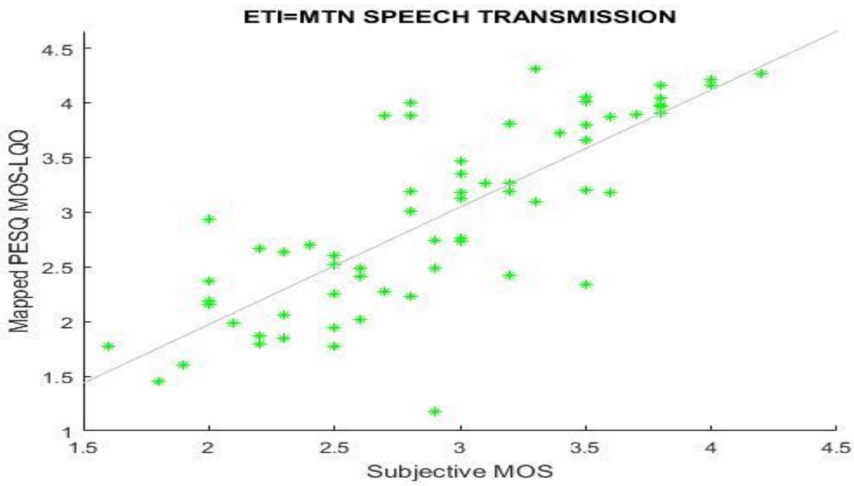

Figure 5: Scatter/regression plots (ETI-MTN)

The correlation coefficients of fitting the objective quality score to the subjective quality score for the various transmission conditions or networks as in this case, was obtained using the Pearson's coefficient equation given by (17):

$$R = \frac{\sum_{i=1}^{N}(x_i - \bar{x})\sum_{i=1}^{N}(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(y_i - \bar{y})^2}} \quad (9)$$

The obtained coefficient correlation figures of merit for each of the three network speech transmissions are shown in table 2.

Table 2: Correlation Coefficients Subjective vs. PESQ MOS-LQO.

Networks	GLO – GLO	ETI – ETI	ETI – MTN
Correlation Coefficient, R	0.77	0.81	0.75

VII. Conclusion

Approaches for perceptive quality of assessment of speeches transmitted over telecommunication networks were considered with particular focus on intrusive objective quality assessment methods. Recorded speech samples were transmitted over two intra-networks and one inter-network for evaluation purpose for this research work.

Objective methods of speech quality estimation are highly computational but possess very important merits that make them much more desirable over subjective speech quality estimation methods. In this work, the PESQ algorithm was compiled on Dev C++ software to obtain raw MOS scores that were mapped using the Morfitt and Cotanis logistic mapping function that proved more accurate than the ITU-T Rec. P.862.1. The mapped PESQ MOS-LQO scores were correlated with quality scores (MOS) obtained from subjective assessment to determine the figure of merit of the whole research work done.

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A. Olatubosun "Intrusive Assessment Of Speech Quality Over Wireless Networks "IOSR Journal of Electronics and Communication Engineering (IOSR-JECE) 13.5 (2018): 03-12.