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# Performance Analysis of Speech Transmission Over Composite Wireless Channels

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**ABSTRACT**

This study gives an insight into the performance of speech transmission over the state-of-the-art $\kappa-\mu$/inverse and $\eta-\mu$/inverse gamma composite wireless channels. By approximation, novel expressions for the probability density functions, cumulative distribution functions, and moment-generating functions of these composite channels have been derived in the form of finite series summations. The comparative results are simple to implement, as well as, it eliminates the constraints of the integer value of inverse gamma parameter present in the existing expressions of moment-generating functions in literature. The system performance has been evaluated as average symbol error rate and outage probability. On the other hand, speech signals from the Texas Instruments/Massachusetts Institute of Technology database have been considered for transmission over the derived composite channels. The quality of the received speech signals has been analyzed as a measure of perceptual evaluation of speech quality, short-time objective intelligibility, and segmental signal to noise ratio for different received signal to noise ratios.

***Index Terms*—**Composite channels, speech intelligibility, speech transmission, $\eta-\mu$/inverse gamma, $\kappa-\mu$/inverse gamma

## I. INTRODUCTION

Radio wave propagation in harsh and tough environments is complex and is heavily affected by fading and shadowing phenomena. These radio channels are used to carry data as well as speech information. A number of channel distributions are available in literature to model combined behavior of fading and shadowing which have been termed as composite channels [1]. Besides these, a variety of composite distributions based on general fading models is also proposed and studied [2-12]. Currently two new composite distributions, that is, $\kappa-\mu$/inverse gamma and $\eta-\mu$/inverse gamma, have been reported and empirically validated through field measurements [13]. Inverse gamma function can be defined by the integral:

$$\Gamma(a,z)=\int_{z}^{\infty} t^{(a-1)}e^{-t}dt \tag{1}$$

This mathematical function is suitable for both numerical and symbolic manipulations. Inverse gamma distribution can be understood as bi-parameter continuous probability distributions on positive real line, and more precisely, it is the reciprocal distribution of a gamma-distributed variable.

Inverse gamma (IG) distribution is invariably employed in Bayesian analysis, in which distribution is derived as marginal posterior distribution of unknown variance for normal distribution, in case of uninformative prior utilized, and as analytically tractable conjugate prior, if informative prior is needed.

The various terms like probability density functions (PDFs), cumulative distribution function (CDFs), and moment-generating functions (MGFs) will be introduced briefly before going into further details of the research work.

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The integral of the PDF gives the probabilities related to a continuous random variable. In graphical representation, it can be visualized as the total area of the curve above the *x* axis upto 1. The probability that the outcome of observation lies between any two values as specified by the PDF is the percentage of curve area included between those two values. Each random variable is definitely associated with a PDF.

Cumulative distribution function is a function that gives the cumulative probability of a given value of a variable. The CDF is used to determine that a random value taken from a population will be either equal to or less than a certain specified value. This provides a measure to determine the probability that a specific observation will be greater than or between the two values.

Moment-generating function is a function that uniquely decides the probability distribution of a random variable. It serves as an alternative description of probability distribution for a random variable. This function is utilized to compute a distribution's moments: the nth moment about 0 is the nth derivative of the moment-generating function, evaluated at 0. In addition to univariate distributions, these functions can be determined for vector-valued random variables and can even be extended to more general cases. It must be noted that MGF does not necessarily exist for a real-valued distribution.

The expression for PDFs, CDFs, and MGFs of distributions derived in [13] is represented as infinite series submissions which are difficult to implement and analyze. Speech transmission over these channels gives distorted version of received speech as compared to the transmitted one. Speech quality assessment is the tool that judges the quality of received speech signals. The assessment can be performed either through subjective or objective tests [14]. Subjective testing requires trained human listeners; therefore, they are time-consuming and expensive. Due to human-intensive nature of subjective testing, researchers and engineers use objective methods that have high correlation with subjective rating scores [15]. Perceptual evaluation of speech quality (PESQ) has been recommended by ITU-T P.862 as a quality assessment measure for wide range of network conditions [16]. Composite measures can also be utilized to evaluate the quality of speech received [15]. Though, on the receiver side, received speech passes through a denoising algorithm to enhance the speech quality [17-19], this study does not use any such algorithm, as the aim of this research is only to analyze the performance of speech transmission over aforementioned composite channels.

Speech recognition with artificial intelligence is hard to implement with certain accuracy, in real-time environment due to various challenges like lack of lingual knowledge, background environment noise, imperfect output, punctuation placement, timing of words, speaker identification, echo, Speaker accents, domain specific technology, and data privacy.

In this study, first, approximate expressions for PDFs, CDFs, and MGFs of $\kappa-\mu$ / IG and $\eta-\mu$ / IG composite channels have been obtained. The acquired expressions are obtained as finite series summations and are simpler to implement compared to the expressions derived in [13]. The derived expressions for MGFs also have the advantage in that these expressions eliminate the constraints of integer value of inverse gamma parameter in the expressions of MGFs for $\kappa-\mu$/inverse gamma and $\eta-\mu$/inverse gamma channels derived in literature [13, Eq. 13]. The derived expressions have been used to derive average symbol error rate and outage probability for peer-to-peer communication links. Finally, a set of 20 phonetically balanced speech signals (10 male, 10 female) have been considered from the Texas Instruments/Massachusetts Institute of Technology (TIMIT) database [20] for transmission and PESQ, short-time objective intelligibility (STOI) [21], and segmental signal to noise ratio (SNR) [22] have been applied to estimate the quality of received speech signals in comparison to the transmitted ones.

The other sections of the study are organized as follows: section II encompasses the derivation of statistical characteristics for $\kappa-\mu$ / IG and $\eta-\mu$ / IG channels. System model is explained in section III. Section IV discusses the performance matrices for channel as well as speech. Section V covers the results and discussions. Lastly, section VI concludes the study.

## II. THE $\eta-\mu$/INVERSE GAMMA AND $\kappa-\mu$/INVERSE GAMMA COMPOSITE CHANNELS

Probability density function of inverse gamma random variable (τ) along with mean (τ) equals unity and scale parameter $\beta$ is given as:

$$f_\tau(\tau)=\frac{\beta^{\beta+1}}{\Gamma(\beta+1)}\tau^{-\beta-2}\exp\left(-\frac{\beta}{\tau}\right) \tag{2}$$

Probability density functions of instantaneous SNRs ($\gamma$) s for $\eta-\mu$/IG and $\kappa-\mu$/IG composite channels can be calculated by taking averages of the PDFs of instantaneous SNRs of $\eta-\mu$ and $\kappa-\mu$ distributions [23] over (1) as given in the following equations:

$$\begin{aligned} f_1(\gamma)=\int_0^\infty &\frac{2\sqrt{\pi}\mu^{\mu+\frac{1}{2}}h^\mu\beta^{\beta+1}}{\bar{\gamma}\Gamma(\mu)\Gamma(\beta+1)H^{\mu-\frac{1}{2}}}\left(\frac{\gamma}{\bar{\gamma}}\right)^{\mu-\frac{1}{2}}\tau^{-\mu-\beta-\frac{5}{2}} \\ &\times e^{-\frac{2\mu h\gamma}{\tau\bar{\gamma}}-\frac{\beta}{\tau}}I_{\mu-\frac{1}{2}}\left(\frac{2\mu H\gamma}{\tau\bar{\gamma}}\right)d\tau \end{aligned} \tag{3}$$

and

$$\begin{aligned} f_2(\gamma)=\int_0^\infty &\frac{\mu\beta^{\beta+1}(1+\kappa)^{\frac{\mu+1}{2}}}{\bar{\gamma}\Gamma(\beta+1)\kappa^{\frac{\mu-1}{2}}e^{\mu\kappa}}\left(\frac{\gamma}{\bar{\gamma}}\right)^{\frac{\mu-1}{2}}\tau^{-\frac{\mu}{2}-\beta-\frac{5}{2}} \\ &\times e^{-\frac{\mu(1+\kappa)\gamma}{\tau\bar{\gamma}}-\frac{\beta}{\tau}}I_{\mu-1}\left(2\mu\sqrt{\frac{\kappa(1+\kappa)\gamma}{\tau\bar{\gamma}}}\right)d\tau \end{aligned} \tag{4}$$

The symbols in the above equations have their usual meanings [23]. Expressions of PDFs for $\kappa-\mu$/IG and $\eta-\mu$/IG composite channels can be acquired by solving above equations, whereas the expressions for MGFs ($\Psi(\cdot)$) can be obtained by definition $E[e^{s\gamma}]$. The expressions of CDFs can be obtained by definition $L^{-1}(\Psi(-s)/s;\gamma)$. These expressions are given by the following Lemmas.

Lemma 1: The PDF for instantaneous *SNR* ($\gamma$) of $\eta-\mu$/inverse gamma composite channel is

$$f_1(\gamma) \approx \frac{2A\sqrt{\pi}\mu^{\mu+\frac{1}{2}}\left(h^2-H^2\right)^{\mu}}{\beta^{\mu+\frac{1}{2}}\bar{\gamma}\Gamma(\mu)H^{\mu-\frac{1}{2}}}\left(\frac{\gamma}{\bar{\gamma}}\right)^{\mu-\frac{1}{2}} \times \sum_{i=0}^{N} w_i x_i^{\mu+\beta+\frac{1}{2}} e^{-\frac{2\mu h\gamma x_i}{\beta\bar{\gamma}}} I_{\mu-\frac{1}{2}}\left(\frac{2\mu H\gamma x_i}{\beta\bar{\gamma}}\right) \quad (5)$$

where $w_i$ and $x_i$ refers to the weights and nodes of Gauss–Laguerre integral approx., $N$ is the number of terms and $A=\left[\sum_{i=0}^{N} w_i x_i^{\beta}\right]^{-1}$.

Proof: On substituting $\beta/\tau = x$ in (2) and employing Gauss–Laguerre integral approx., PDF of $\eta-\mu$/ig composite channel is calculated and given as (4). The equation is multiplied by a normalization constant to ensure $\int_0^{\infty} f_{\gamma}(t)dt = 1$ and with some mathematics and from [24, Eq. 3.15.1.3], it is given as $A\Gamma(\beta+1)\left(h^2-H^2\right)^{\mu}/h^{\mu}$.

Lemma 2: The PDF for instantaneous *SNR* ($\gamma$) of $\kappa-\mu$/IG composite channel is

$$f_2(\gamma) \approx \frac{A\mu(1+\kappa)^{\frac{\mu+1}{2}}}{\beta^{\frac{\mu+1}{2}}\bar{\gamma}\kappa^{\frac{\mu-1}{2}}e^{\mu\kappa}}\left(\frac{\gamma}{\bar{\gamma}}\right)^{\frac{\mu-1}{2}} \sum_{i=0}^{N} w_i x_i^{\frac{\mu}{2}+\beta+\frac{1}{2}} \times e^{-\frac{\mu(1+\kappa)\gamma x_i}{\beta\bar{\gamma}}} I_{\mu-1}\left(2\mu\sqrt{\frac{\kappa(1+\kappa)\gamma x_i}{\beta\bar{\gamma}}}\right) \quad (6)$$

where $x_i$, $w_i$, $N$, and A are same as in Lemma 1.

Proof: On substituting $\beta/\tau = x$ in (3) and utilizing Gauss–Laguerre integral approx., PDF for $\kappa-\mu$/IG composite channel can be calculated and given by (5). The equation is multiplied by a normalization constant to ensure $\int_0^{\infty} f_{\gamma}(t)dt = 1$ and with some mathematics and from [24, Eq. 3.15.2.8] it is given as $A\Gamma(\beta+1)$.

Lemma 3: *MGF* of $\eta-\mu$/inverse gamma composite channel is

$$\Psi_1(s) = \sum_{i=0}^{N} w_i x_i^{2\mu+\beta} A\left(4\mu^2\left(h^2-H^2\right)\right)^{\mu} \times \left(2\mu(h-H)x_i - s\beta\bar{\gamma}\right)^{-\mu} \times \left(2\mu(h+H)x_i - s\beta\bar{\gamma}\right)^{-\mu} \quad (7)$$

The symbols in above equations have their usual meanings.

Proof: On substituting (4) in the definition of MGF and using [24, Eq. 3.15.1.3], MGF for $\eta-\mu$/ IG composite channel as per (6) can be evaluated.

Lemma 4: The MGF for $\kappa-\mu$/inverse gamma composite channel is

$$\Psi_2(s) = \sum_{i=0}^{N} w_i x_i^{\mu+\beta} A\left(\frac{\mu(1+\kappa)}{\mu(1+\kappa)x_i - s\beta\bar{\gamma}}\right)^{\mu} \times e^{\frac{\mu^2\kappa(1+\kappa)x_i}{\mu(1+\kappa)x_i - s\beta\bar{\gamma}} - \mu\kappa} \quad (8)$$

where symbols in the above equation have their usual meanings.

Proof: On substituting (5) in the definition of MGF and using [24, Eq. 3.15.2.8], MGF of $\kappa-\mu$/inverse gamma composite channel as per given by (7) can be evaluated.

Lemma 5: *CDF* of $\eta-\mu$/inverse gamma composite channel is

$$F_1(\gamma) = \frac{A\left(h^2-H^2\right)^{\mu}}{\Gamma(2\mu+1)}\left(\frac{2\mu\gamma}{\beta\bar{\gamma}}\right)^{2\mu} \sum_{i=0}^{N} w_i x_i^{2\mu+\beta} \times f_2\left(\mu,\mu;2\mu+1;-\frac{2\mu(h-H)x_i\gamma}{\beta\bar{\gamma}}, -\frac{2\mu(h+H)x_i\gamma}{\beta\bar{\gamma}}\right) \quad (9)$$

where $f_2(\cdot)$ refers to the hypergeometric function of two variables.

Proof: On substituting (6) in the definition of CDF and using [25, Eq. 2.1.3.1], CDF for $\eta-\mu$/Inverse Gamma composite channel as provided by (8) can be evaluated.

Lemma 6: *CDF* of $\kappa-\mu$/inverse gamma composite channel is

$$F_2(\gamma) = \frac{Ae^{-\mu\kappa}}{\Gamma(\mu+1)}\left(\frac{\mu(1+\kappa)\gamma}{\beta\bar{\gamma}}\right)^{\mu} \sum_{i=0}^{N} w_i x_i^{\mu+\beta} \times e^{-\frac{\mu(1+\kappa)\gamma x_i}{\beta\bar{\gamma}}} f_3\left(1;\mu+1;\frac{\mu(1+\kappa)x_i\gamma}{\beta\bar{\gamma}}, \frac{\mu^2\kappa(1+\kappa)x_i\gamma}{\beta\bar{\gamma}}\right) \quad (10)$$

where $f_3(\cdot)$ refers to the hypergeometric function of two variables. Proof: On substituting (7) in the definition of CDF and using [25, Eqs. 1.1.1.2 and 2.2.3.16], CDF for $\kappa-\mu$/inverse gamma composite channel as per (9) can be evaluated.

## III. THE COMMUNICATION SYSTEM MODEL

The communication model cited in this study is depicted in Fig. 1. The essential components of a communication system are information

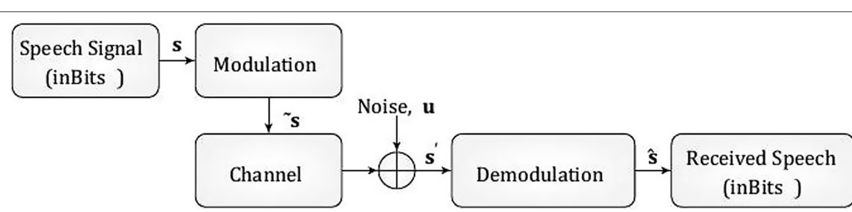


**Fig. 1.** Basic speech communication system model.

source/speech signal, modulator and transmitter, communication channel, demodulator, and receiver. The speech signal originated is modulated employing various modulation schemes in the modulation block which is then transmitted through the channel during which it is contaminated by noise. The signal is received and demodulated at the receiver end, and final extraction of signal is done where different technologies are employed to filter clear speech from the added noise during channel transmission. The message bit stream containing speech signals is modulated and is further transmitted over the communication channel. The communication channel in the system model is modeled either by $\eta-\mu$/IG or by $\kappa-\mu$/IG composite distribution. On the receiver side, the Additive White Gaussian Noise (AWGN) noise **u** is appended to the signals resulting **s′** which after demodulation results in **ŝ**. In the end, the average Bit Error Rate (BER) is determined by the message and received bits. **s, u,** and **s′** are specified as

$$\begin{aligned} \mathbf{s} &= \left[ s_i : s_i \in \{0,1\}, \forall i \in I^+ \right] \\ \mathbf{u} &= \left[ u_i : u_i \sim N\left(0,\sigma^2\right)\right]' \\ \mathbf{s}' &= \mathbf{h}\tilde{\mathbf{s}} + \mathbf{u} \end{aligned} \tag{11}$$

where ~ **s** is the mapped version of **s** after modulation and h refers to the diagonal matrix having diagonal elements $h_{ii}$, referring to random variables with $\kappa-\mu$/inverse gamma or $\eta-\mu$/inverse gamma composite distribution. Finally, ASER ( $\Lambda$ ) can be considered as the measure of the system performance. Received speech quality is measured with various objective quality measures elucidated in next section.

**TABLE I.** AVERAGE OF ASERS AND SPEECH QUALITY MEASURES FOR 20 DIFFERENT RECEIVED AUDIO QPSK-MODULATED SIGNALS OVER $\eta-\mu$/INVERSE GAMMA AND $\kappa-\mu$/ INVERSE GAMMA COMPOSITE CHANNELS WITH PARAMETERS $Z$ = [3,6,2] AND $Z$ = [8,6,2], RESPECTIVELY.

| Channel | SNR | ASER | PESQ | STOI | Seg. SNR |
|---|---|---|---|---|---|
| $\eta-\mu$/inverse gamma | 10 dB | $2.44\times10^{-02}$ | 09,829 | 05,225 | ⁻59,371 |
| | 12 dB | $8.21\times10^{-03}$ | 12,567 | 06,061 | 22,649 |
| | 14 dB | $2.12\times10^{-03}$ | 15,628 | 07,751 | 19.2 164 |
| | 16 dB | $3.84\times10^{-04}$ | 27,136 | 09,086 | 2,74,758 |
| | 18 dB | $4.92\times10^{-05}$ | 43,704 | 09,997 | 2,95,990 |
| | 20 dB | $5.79\times10^{-06}$ | 45,000 | 10,000 | 2,97,538 |
| $K-\mu$/inverse gamma | 10 dB | $1.99\times10^{-02}$ | 09,956 | 05,178 | ⁻64,769 |
| | 12 dB | $5.91\times10^{-03}$ | 12,870 | 05,811 | ⁻00,035 |
| | 14 dB | $1.23\times10^{-03}$ | 14,382 | 07,161 | 1,33,726 |
| | 16 dB | $1.82\times10^{-04}$ | 24,125 | 08,662 | 2,54,350 |
| | 18 dB | $1.17\times10^{-05}$ | 36,937 | 09,726 | 2,91,337 |
| | 20 dB | $0.00\times10^{-06}$ | 44,821 | 09,999 | 2,97,405 |

SNR, signal to noise ratio; ASER, average symbol error rate; PESQ, perceptual evaluation of speech quality; STOI, short-time objective intelligibility.

## IV. PERFORMANCE EVALUATION

### A. Average Symbol Error Rate

Average symbol error rate (ASER) for various coherent detection schemes over the arbitrary channels with distribution D is given as follows:

$$\Lambda_{\mathcal{D}}\left(\bar{\gamma}\right) = \frac{2A_c}{\pi}\int_0^{\pi/2}\Psi_{\mathcal{D}}\left(-\frac{B_c}{\sin^2(\delta)}\right)d\delta \tag{12}$$

where $A_c$ and $B_c$ for different modulation schemes are given in [26, Table I] and $D\in\{1, 2\}$. Expressions for ASERs of both channels can be provided by the following Lemmas.

Lemma 7:*ASER* for various coherent detection schemes over $\eta-\mu$/inverse gamma channel is

$$\begin{aligned} \Lambda_1\left(\bar{\gamma}\right) = {} & \frac{A_c A\Gamma\left(2\mu+\frac{1}{2}\right)\left(h^2-H^2\right)^{\mu}}{\sqrt{\pi}\Gamma\left(2\mu+1\right)h^{\mu}}\sum_{i=0}^{N} w_i x_i^{2\mu+\beta}\left(4\mu^2 h\right)^{\mu} \\ & \times\left(2\mu\left(h-H\right)x_i + B_c\beta\bar{\gamma}\right)^{-\mu} \\ & \times\left(2\mu\left(h+H\right)x_i + B_c\beta\bar{\gamma}\right)^{-\mu} \\ & \times F_1\left(\frac{1}{2},\mu,\mu;2\mu+1;\frac{2\mu\left(h-H\right)x_i}{2\mu\left(h-H\right)x_i+B_c\beta\bar{\gamma}}\right. \\ & \left.\frac{2\mu\left(h+H\right)x_i}{2\mu\left(h+H\right)x_i+B_c\beta\bar{\gamma}}\right) \end{aligned} \tag{13}$$

where $F_1$ (•) is Appell's hypergeometric function [27, Eq. 16.15.1].

Proof: By Substituting (6) in (13) and following similar procedure as described in [28], (14) is given below.

Lemma 8: The ASER of various coherent detection schemes over the $\kappa-\mu$/inverse gamma channel is

$$\begin{aligned} \Lambda_2\left(\bar{\gamma}\right) = {} & \frac{A_c A(\mu(1+\kappa))^{\mu}\Gamma\left(\mu+1/2\right)\sqrt{B_c\beta\bar{\gamma}}}{\sqrt{\pi}\Gamma\left(\mu+1\right)e^{\mu\kappa}} \\ & \times\sum_{i=0}^{N}\frac{w_i x_i^{\mu+\beta}}{\left[\mu\left(1+\kappa\right)x_i + B_c\beta\bar{\gamma}\right]^{\mu+1/2}} \\ & \times f_1\left(\mu+\frac{1}{2},1,\mu+1;\frac{\mu\left(1+\kappa\right)x_i}{\mu\left(1+\kappa\right)x_i+B_c\beta\bar{\gamma}}\right. \\ & \times\left.\left(\frac{\mu^2\kappa\left(1+\kappa\right)x_i}{\mu\left(1+\kappa\right)x_i+B_c\beta\bar{\gamma}}\right)\right. \end{aligned} \tag{14}$$

where $\Phi_1$ (•) is confluent hypergeometric function of two variables [28, Eq. 16]. Proof: Substituting (7) in (13) and following similar procedure as described in [28], (15) is given below.

### B. Outage Probabilities

The outage probability $P_{out}$ can be defined as the CDF evaluated at $\gamma_0$ and hence can be explained by following corollary. Corollary 1: The outage probability for $\kappa-\mu$/ IG & $\eta-\mu$/ IG channels is

$$P_{out} = F_i(\gamma_0),\ i\in\{1, 2\} \tag{15}$$

Proof: (16) can be directly interpreted from the definition of outage probability.

### C. Speech Quality Assessment

In order to measure the performance of speech over $\kappa - \mu$/IG & $\eta - \mu$/IG composite channels, a set of 20 phonetically balanced speech signals (10 male, 10 female) have been considered from the TIMIT database for transmitting through aforementioned channels. Furthermore, these speech signals are down-sampled to telephony bandwidth which is valued at 8 kHz, where the length of each sentence is around 6 seconds long. For the objective quality assessment, PESQ, STOI, and segmental SNR were considered. Short-time objective intelligibility and PESQ are firmly related to human auditory perception and are being extensively utilized in speech quality assessment criteria. Therefore, STOI and PESQ are the best choices for speech quality assessment. The PESQ algorithm predicts subjective opinion scores of a degraded audio sample. Perceptual evaluation of speech quality scores range from 4.5 to −0.5, with higher scores indicating better quality [29]. The STOI metric is derived from correlation coefficient of temporal envelopes of time-aligned reference and processed speech signal in short-time overlapped segments. The STOI is basically a metric to speculate/forecast intelligibility of the noisy speech. This method is based on subjective intelligibility tests (asking for recognized word/syllables/logatoms, etc.).

## V. RESULTS AND DISCUSSION

The number of terms *N* in the expressions governs the computation overheads to arrive at numerical values of average BERs and outage probabilities and their accuracy. The value of *N* is inversely proportional computational burden but directly affected by the accuracy of results. The choice of the number of terms *N* is a trade-off between the requirement of accuracy depending upon the application and the computing resources available. As an example at 10 dB average SNR, the min number of terms required for convergence of average BERs and outage probabilities ($\gamma_0 = 5$ dB) to achieve an accuracy of fourth significant digits for $\kappa - \mu$/inverse gamma composite channel with parameter set $\zeta = [\kappa, \mu, \beta]$ =[8, 6, 2] and $\eta - \mu$/inverse gamma composite channel with parameter set $\zeta = [\eta, \mu, \beta]$ =[3, 6, 2] is 10 and 8 and 14 and 10, respectively. The number of terms for other parameter sets will vary accordingly as per required accuracy of the application.

Digital phase modulation is a versatile and widely accepted method of wirelessly transferring digital data. Digital modulation schemes, namely, Quadrature Phase Shift Keying (QPSK) and Binary Phase Shift Keying (BPSK) are quiet popular in the wireless transmission domain. Binary Phase Shift Keying scheme transmits data by altering, or modulating, two phases of the carrier wave. The max phase difference in this modulation scheme is 180°. Constellation points have uniform angular spacing around a circle providing max phase separation and best immunity to degradation of signal. Quadrature Phase Shift Keying scheme transmits data by altering or modulating four phases of the carrier wave. The max phase difference in this modulation scheme is 90°, sometimes called quadri-phase or quaternary phase shift keying. Binary Phase Shift Keying transmits one bit per symbol, while, in case of QPSK, 2 bits per symbol are transmitted.

Qualitatively average error symbol rate (AESR) is the average probability of receiving a symbol in error. In case of wireless transmission, the SER is the percentage of symbols that have errors relative to the total number of symbols received in a transmission, usually expressed as ten to a negative power.

Outage probability is basically an indication of the quality of the communication channel. Outage probability is defined as the probability that information rate is less than the required threshold information rate. It is the probability that an outage will occur within a specified time period. Alternatively, it can be specified as probability that the target SINR for a user is not achieved [30]. It is measured by finding the probability that a specific transmission rate is not supported.

Figure 2 depicts the ASERs wrt average SNR for various modulation schemes in wireless communication system over $\kappa - \mu$/inverse gamma and $\eta - \mu$/inverse gamma channels with representative parameter sets $\zeta = [8, 6, 2]$ and $\zeta = [3, 6, 2]$, respectively. As depicted in the Fig. 2, it is evident that best performance can be achieved through BPSK modulation system and performance starts degrading for higher-level constellations. More precisely, ASERs over $\kappa - \mu$/inverse gamma channel are $8 \times 10^{-6}$, $4 \times 10^{-4}$, $1.8 \times 10^{-1}$, and $1.7 \times 10^{-1}$ approximately for BPSK, QPSK, 8PSK, and 16PSK modulated systems respectively, whereas ASERs over $\kappa - \mu$/inverse gamma channel are $1.5 \times 10^{-6}$, $1.8 \times 10^{-4}$, $1.4 \times 10^{-2}$, and $1.6 \times 10^{-1}$ approximately for BPSK, QPSK, 8PSK, and 16PSK modulated systems, respectively [31].

Figure 3 depicts the Average Bit Error Rates (ABER)wrt average SNR for BPSK modulated wireless communication system over $\kappa - \mu$/IG channels and $\eta - \mu$/IG with different channel parameters. As is clear from Fig. 3, for $\eta - \mu$/IG channel, average BER is directly proportional to $\eta$, whereas it is inversely proportional to $\mu$ and $\beta$. As an example considering an average SNR of 14 dB, ABER rises from $7 \times 10^{-5}$ to $8 \times 10^{-5}$ approximately if $\eta$ goes up from 3 to 4, whereas ABER falls down from $8 \times 10^{-5}$ to $6.5 \times 10^{-5}$ approximately and $6.5 \times 10^{-5}$ to $3.8 \times 10^{-5}$ approximately if $\mu$ rises from 6 to 7 and $\beta$ rises from 2 to 2.5 respectively keeping other parameters constant or unchanged. For $\kappa - \mu$/IG channel, ABER drops with rise in other various channel parameters. As an example for an average SNR of 14 dB, ABER drops from $6.5 \times 10^{-5}$ to $5 \times 10^{-5}$ approximately if $\kappa$ rises from 7 to 8, it drops from $5 \times 10^{-5}$ to $3.5 \times 10^{-5}$ approximately if $\mu$ rises from 6 to 7, whereas it drops from $3.5 \times 10^{-5}$ to $1.5 \times 10^{-5}$ approximately, if $\beta$ rises from 2 to 2.5 keeping various other parameters constant and unchanged. It is pertinent to note that for both types of channels, ABERs differ very less on increasing the fading parameters, while if the variation is there in the shadowing parameter $\beta$, a large variation is observed in the ABER.

Figure 4 depicts the outage probabilities for $\gamma_0 = 5$ dB and different values of $\gamma$ taking into account different parameters $[\eta, \mu, \beta]$ and $[\kappa, \mu, \beta]$ of $\kappa - \mu$/IG and $\eta - \mu$/IG channels respectively. It is quite evident from Fig. 4 that for the selected parameters, $\kappa - \mu$/inverse gamma channel has lower outage probabilities than $\eta - \mu$/inverse gamma channel. It is also observed that for $\kappa - \mu$/inverse gamma channel, the outage probability diminishes with rise in the values of all parameters. However, if we consider the $\eta - \mu$/inverse gamma channel, it diminishes with the rise in values of $\mu$ and $\beta$ and rise with rise in value of $\eta$.

Table I depicts the average of ASERs and speech quality measures for 20 different received audio QPSK-modulated signals over $\kappa - \mu$/inverse gamma and $\eta - \mu$/inverse gamma and composite channels with parameters $\zeta = [8, 6, 2]$ and $\zeta = [3, 6, 2]$ respectively. Whereas, the pictorial representations of the transmitted and received signals at 12,16, and 20 dB SNRs for one of the speech samples are shown in

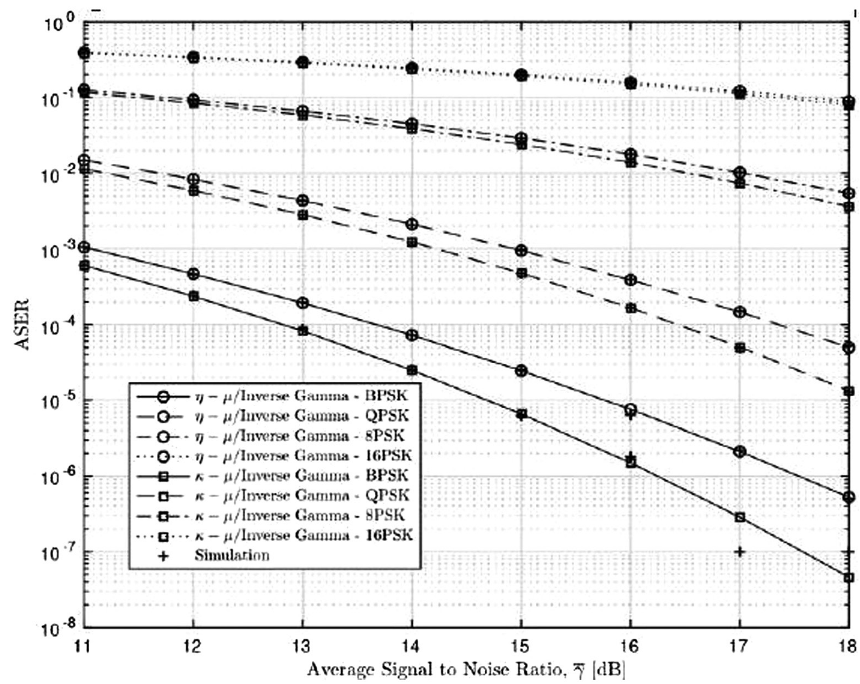


**Fig. 2.** ASER for various modulation schemes of wireless communication system over $\eta-\mu$/inverse gamma and $\kappa-\mu$/inverse gamma channels with typical parameter sets $\zeta = [3, 6, 2]$&$\zeta = [8, 6, 2]$, respectively.

Figs. 5 and 6, respectively. Speech quality measures for different modulations and other parameters of the channel can be obtained similarly, though the trend remains same. It is obvious and also reflects in Table I and Figs. 5 and 6 that speech quality improves if received SNR increases. For example, over $\eta-\mu$/inverse gamma channel with parameters $\zeta = [3, 6, 2]$, if received SNR increases from 10 dB to 20 dB, mean PESQ increases from 0.9829 to 4.5, STOI score improves from 0.5225 to 1, and segmented SNR improves from 0.5178 to 0.9999, and segmented SNR increases from –6.4769 to 29.7405. Although the system performance degrades by lowering the SNR conditions

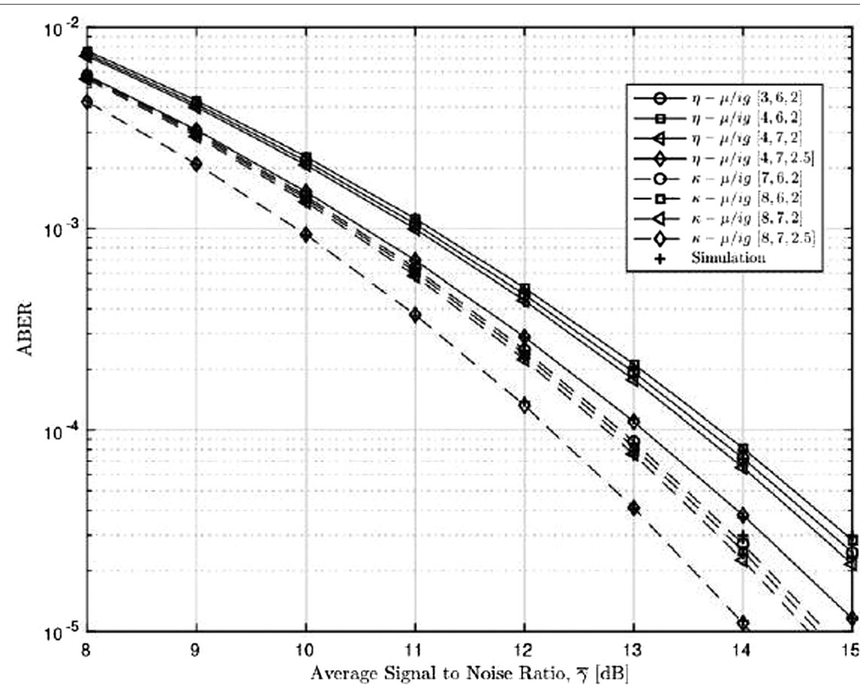


**Fig. 3.** ABERs for BPSK-modulated wireless communication system over $\eta-\mu$/inverse gamma and $\kappa-\mu$/inverse gamma channels with different channel parameters.

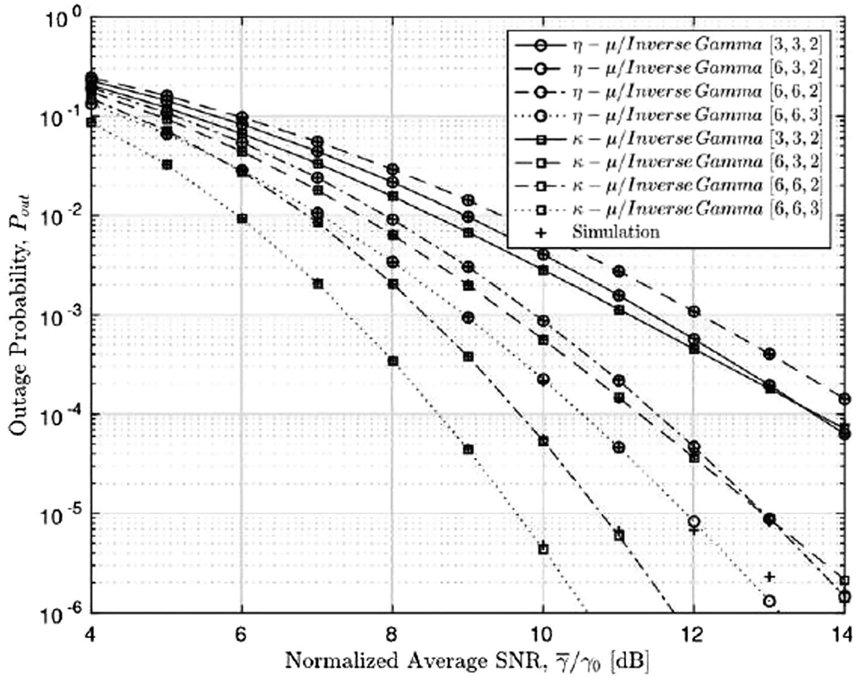


**Fig. 4.** Outage probabilities at $\gamma_0 = 5$ dB and different values of $\gamma$ for different parameters [$\eta$, $\mu$, $\beta$] and [$\kappa$, $\mu$, $\beta$] of $\eta-\mu$/inverse gamma and $\kappa-\mu$/inverse gamma channels, respectively.

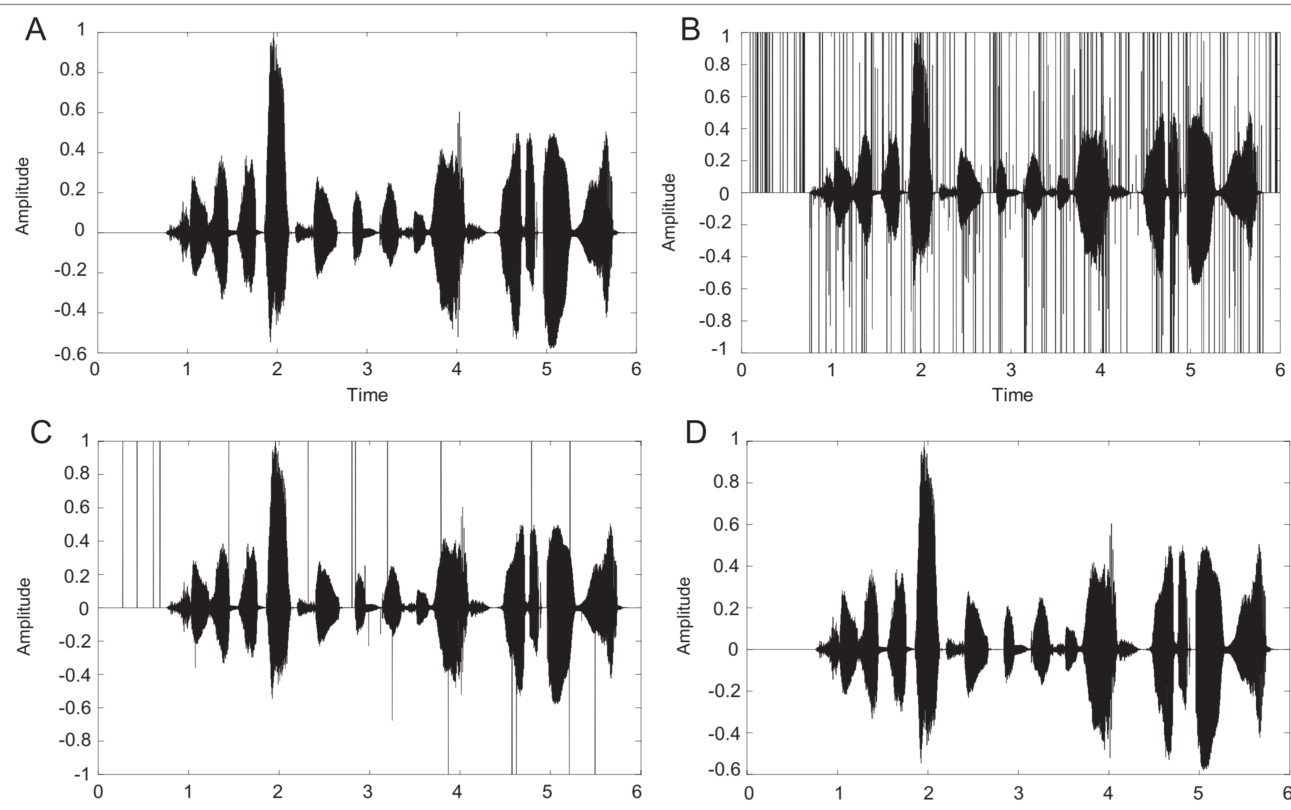


**Fig. 5. A-D.** Speech samples over $\eta-\mu$/inverse gamma composite channel with parameters $\zeta$ = [3,6,2], (A) transmitted speech, (B) received speech at 12 dB SNR, (C) received speech at 16 dB SNR, (D) received speech at 20 dB SNR.

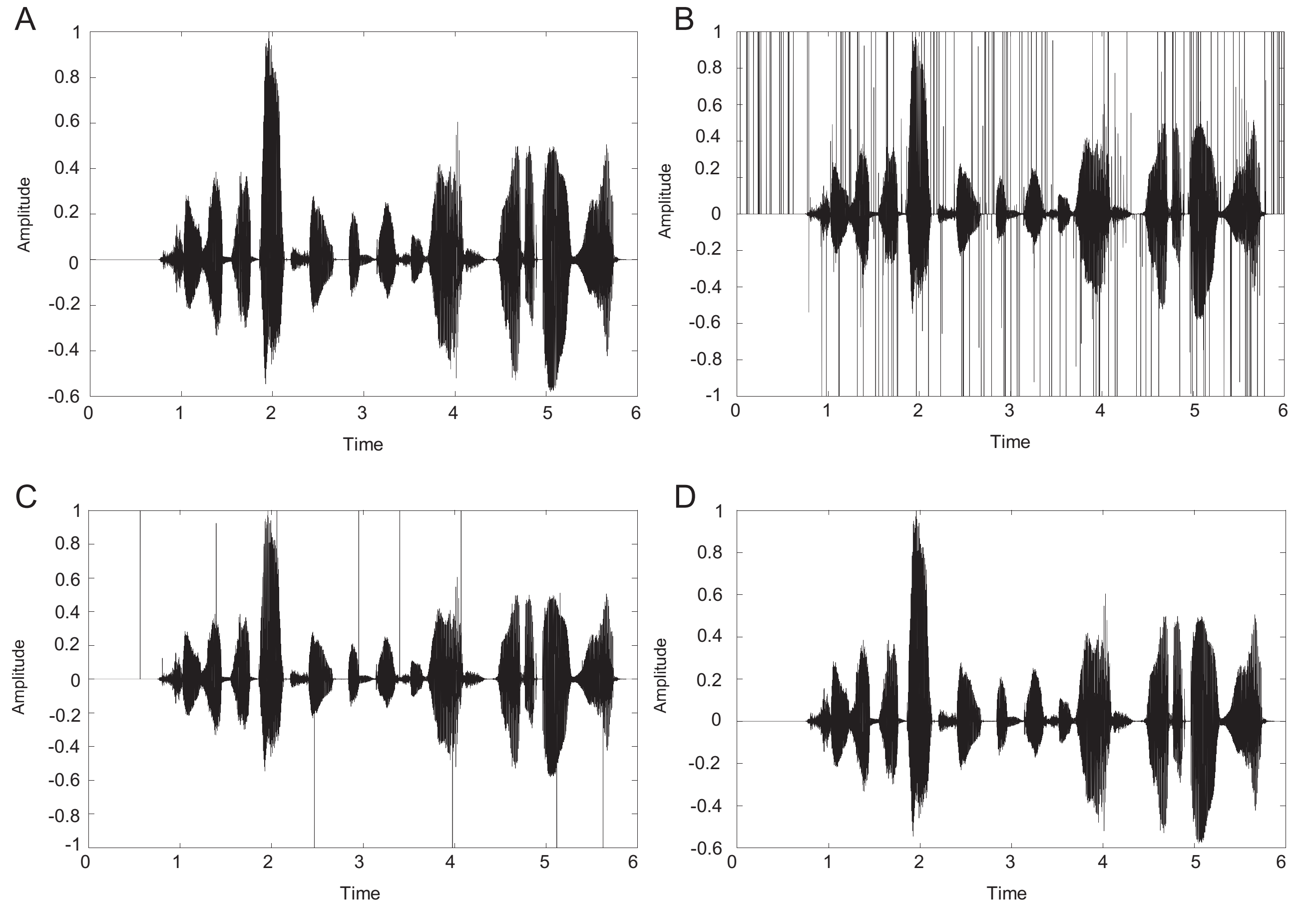


**Fig. 6. A-D.** Speech samples over $\kappa - \mu$/inverse gamma composite channel with parameters $\zeta$ = [8,6,2], (A) transmitted speech, (B) received speech at 12 dB SNR, (C) received speech at 16 dB SNR, (D) received speech at 20 dB SNR.

(<10 dB), it promises improved speech quality, especially when the SNR conditions increase over 12 dB. Similar performances have been judged from Fig. 2, 3, and 4, where the ASERs and outage probability for various parameters have been given. Table I presents the average of ASERs and speech quality measures for 20 different received audio QPSK-modulated signals over $\kappa - \mu$/inverse gamma and $\eta - \mu$/inverse gamma composite channels with parameters $\zeta = [8, 6, 2]$ and $\zeta = [3, 6, 2]$, respectively, increases from –5.9371 to 29.7538. Similarly, for $\kappa - \mu$/inverse gamma composite channels with parameters $\zeta = [8, 6, 2]$, if received SNR increases from 10 dB to 20 dB, mean PESQ increases from 0.9956 to 4.4821 STOI score.

## VI. CONCLUSION

This study investigates speech transmission through the composite wireless channels by deriving new expressions for the PDFs, CDFs, and MDFs for the $\kappa - \mu$//inverse and $\eta - \mu$//inverse gamma composite wireless channels. These derived composite channels have been evaluated and the performance in terms of ASERs and outage probabilities has been analyzed. On the other hand, the quality of the transmitted speech signals has been measured by state-of-art speech quality measures, that is the PESQ, STOI, and segmental SNRs. A total of 20 speech samples (10 male and 10 female samples) have been considered for experimental validations. The results are encouraging and clearly indicate that both the $\kappa - \mu$//inverse and $\eta - \mu$//inverse gamma composite wireless channels outperformed and better speech quality was achieved at the receiver end especially when the input SNR was over and above 12 dB. After focusing on successful experimental validation and speech transmission, this work will take a way forward for implementing the setup in real-time scenario to filter the noise signals from the received speech signals [17] and transmit the same through $\kappa - \mu$//inverse and $\eta - \mu$//inverse gamma composite wireless channels as described in this study.

**Code Availability:** The Code will be made available on reasonable request.

**Data Availability:** There is no associated data for this manuscript.

**Peer-review:** Externally peer-reviewed.

**Author Contributions:** Concept – N.S., A.G.; Design – N.S., A.G., M.K.S.; Supervision – N.S., A.G., A.K.; Data Collection and/or Processing – N.S., A.G., M.K.S., A.K.; Analysis and/or Interpretation – N.S., A.G.; Literature Review – N.S., A.G., M.K.S.; Writing – N.S., A.G.; Critical Review – N.S., A.G., A.K.

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