Stochastic Network Calculus for Gilbert-Elliot Fading in Underwater Wireless Communication

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ABSTRACT

Underwater wireless communication networks applications are growing rapidly in the field of research and applications. The acoustic wave propagation in underwater wireless communications is affected by channel variations, multipath propagation and Doppler shift. These factors will affect the performance of underwater communication. In underwater acoustic channels, analyzing the backlog and delay bounds becomes a critical task. To overcome these, Stochastic Network Calculus (SNC) has given rise to the optimism that it can emerge as an elegant mathematical modeling tool for assessing current network performance especially for use in underwater communication. While SNC is a relatively new theory, it is gaining increasing interest and popularity and researchers have also started applying SNC to performance analysis of various systems. In this work, we have developed an underwater acoustic wireless channel subjected to Gilbert-Elliot Fading Channel. In this work, we have derived stochastic service guarantees for delay requirements, violation probabilities, delay bound and traffic burstiness in the acoustic Physical channel.

INTRODUCTION

Underwater networks hold numerous applications in defense, offshore oil industry, pollution monitoring and other commercial applications [1]. In underwater environment, radio signals are subjected to high attenuation and hence data transmissions are possible only for short distances [2]. Data transmission is mostly done using acoustic waves. Underwater acoustic channel is difficult to model as they experience attenuation, multipath fading and time varying characteristics. Acoustic propagation is nearly 20,000 times lower than the radio channel propagation [3]. Data transmission in underwater communications over a moderate distance would suffer a significant amount of propagation delay. The problem of propagation delay is compounded by the limited bandwidth of the acoustic communication medium. Multipath fading is one such phenomenon in acoustic communication that affects the acoustic signal transmitted through acoustic wireless transceiver. There are many models to describe fading, such as: Rayleigh Fading, Rician Fading, Nakagami Fading, Weibull distribution and Gilbert-Elliot model. There are many underwater channel models and most of these models are implemented using Ray theory. Galvin and Coates [4] have simulated the acoustic channel using the deterministic property of the channel and this model failed to address the physical properties of the underwater channel. In order to model the acoustic channel, appropriate mathematical tools need to be incorporated.

In general, mathematical tools play a major role behind any successful model. Deterministic Network Calculus (DNC) is a theory dealing with the performance guarantees in current networks [5]. With the abstraction of arrival curve for traffic flows and service curve for network elements, it has been widely applied in communication networks in measuring network performance [6]. Network calculus has been developed in two tracks namely Deterministic Network Calculus and Stochastic Network Calculus (SNC)[7]. DNC is used for quality of service analysis in data networks [8]. Traffic arrivals at a networked system are modeled by upper envelope functions. Service guarantees systems like router; link and scheduler are characterized by service curves. Based on service and arrival curves, DNC offers convolution forms that enable the derivation of worst-case performance bounds like backlog, delay and loss factors. The advantage of convolution framework is that...
any number of systems in series can be transformed into a single equivalent system by convolution of the individual systems service curves. DNC is not applicable for deriving performance bound guarantees for wireless communication systems due to their inherent behavior. Data communications in wireless networks are unstable and irregular, and hence it becomes difficult to find the deterministic performance bounds. To implement stochastic service provisioning, the performance bounds needs to be complemented with certain violation probabilities. SNC is one such tool that can be implemented in the design of wireless communication networks and it provides non-deterministic service guarantees.

DNC is applied for performance analysis and resource dimensioning of wireless communication networks by several researchers. In [9] authors proposed a methodology for modeling the worst case dimensioning of cluster tree sensor networks. They derived plug and play expressions for the end-to-end delay bounds, buffering and bandwidth requirements as a function of the WSN Cluster tree and traffic characteristics. In [9], the authors presented a method for computing worst-case delays, buffering and bandwidth requirements while assuming that the sink node can be mobile. Surprisingly, SNC has not applied for any Underwater Wireless Sensor Networks (UWSN). Terrestrial sensor networks differ in many properties, features when compared with UWSN. To the author’s knowledge, this is the first work in creating a SNC mathematical model for UWSN acoustic channel that is subjected to Gilbert-Elliot Fading Channel.

In this paper, we propose a SNC based approach for Quality of Service (QoS) analysis for underwater acoustic communication networks subjected to Gilbert-Elliot Fading Channel. We develop a Stochastic Curve model for Gilbert-Elliot Channel and analyze the traffic carrying capacity for a given guarantee at the flow level. A continuous time ON/OFF data source is considered as the traffic model. Finally, We study the impact of the delay bound violation probability, traffic burstiness, channel memory and the delay requirements. Based on our model, we provide formulas to derive probabilistic delay and backlog bounds in the stochastic arrival curves. The simulation results verify that the tightness of the bounds is good.

The rest of the research article is organized as follows. Section II shows the basic notations, operators and properties of stochastic network calculus. Section III explains underwater acoustic Gilbert-Elliot fading channel using stochastic network calculus. Section IV includes performance analysis bounds. Section V, the simulation results and performance evaluation are explained. Section VI concludes the research article with future work.

Basic Notations Of stochastic Network Calculus:

A. Basic Notations:

Fundamentally SNC has its root from Queuing theory[10]. In this section, the basic notations and concepts of SNC are introduced. A process is defined as the function of time $t$. The various network elements is represented as amount of traffic arriving to the network $A(t)$ (arrival process), the amount of traffic leaving the network $A'(t)$ (departure process), the amount of service provided by the network $S(t)$ (Service process) and the amount of service failed to be provided by the network $I(t)$ (Impairment process). We assumed all process are non-negative and increasing functions and by convention $t = 0$, i.e., $A(0) = A'(0) = S(0) = I(0) = 0$. For any $0 \leq s \leq t$, let $A(s,t) \equiv A(t) - A(s), A'(s,t) \equiv A'(t) - A'(s)$, and $S(s,t) \equiv S(t) - S(s)$ and $I(s,t) \equiv I(t) - I(s)$. By default, $A(0) = A'(0) = S(0) = 0$. We denote by $\mathcal{F}$ the set of non-negative wide-sensing increasing functions, and $\mathcal{F}'$ the set of non-negative decreasing functions,

$$\mathcal{F} = \{f(.): \forall 0 \leq x \leq y, 0 \leq f(x) \leq f(y)\}$$

$$\mathcal{F}' = \{f(.): \forall 0 \leq x \leq y, 0 \leq f(y) \leq f(x)\}$$

For any random variable $X$, its distribution function is denoted by $F_X(x) \equiv Prob(X \leq x)$, belongs to $\mathcal{F}$, and its complementary distribution function, $F'_X(x) \equiv Prob(X > x)$, belongs to $\mathcal{F}'$. During model transform, we put a stronger requirement on the bounding function, denoted by $\tilde{g}$ the set of functions in $\tilde{\mathcal{F}}$. Where, for each function $g(.) \in \tilde{\mathcal{G}}$, its $n$th-fold integration is bounded for any $x \geq 0$ and still belongs to $\tilde{\mathcal{G}}$ for any $n \geq 0$, i.e.,

$$\tilde{\mathcal{G}} = \{g(.): \forall n \geq 0, (\int_x^\infty dy)^n g(y) \in \tilde{\mathcal{G}}\}$$

(1)

B. Operators in Stochastic Network Calculus

The following operations are defined under the $(\min, +)$ algebra and will be used in this work: The $(\min, +)$ convolution of function $f$ and $g$ is [11]

$$(f \otimes g)(x) = \inf_{y \in \mathbb{R}}[f(y) + g(x-y)]$$

The $(\min, +)$ deconvolution of function $f$ and $g$ is
\[(f \ominus g)(t) \equiv \sup_{s \geq 0} \{f(t + s) - g(s)\}\]

We also adopt: \([x]^+ \equiv \min\{x, 0\}, [x]^1 \equiv \min\{x, 1\}\)

The pointwise minimum of \(f\) and \(g\) is

\[(f \wedge g)(x) = \min\{f(x), g(x)\}\]

The pointwise maximum of function \(f\) and \(g\) is

\[(f \vee g)(x) = \max\{f(x), g(x)\}\]

In addition, we shall need the normal convolution for independent case analysis:

The normal convolution of functions \(f\) and \(g\) is

\[(f * g)(x) = \int_0^x f(x - y)dg(y)\] (2)

C. Performance Metrics, Traffic and Server Models:

The following measures are of interest in service guarantee analysis under network calculus [12]:

The backlog \(B(t)\) in the system at time \(t\) is defined as:

\[B(t) = A(t) - A'(t).\] (3)

The delay \(D(t)\) at time \(t\) is defined as:

\[D(t) = \inf\{\tau \geq 0: A(t) \leq A'(t + \tau)\}\] (4)

Stochastic traffic arrival curve and service curves are core concepts in stochastic network calculus. There are different definitions of stochastic arrival curve and stochastic service curve. For traffic arrival models, we have:

**Definition 1:**

The traffic-amount-centric (t.a.c) model

A flow \(A(t)\) is said to have a traffic-amount-centric stochastic arrival curve \(\alpha \in \mathcal{F}\) with bounding function \(f \in \mathcal{F}\), denoted by: \(A \sim \text{t.a.c} < f, \alpha >\).

If for all \(t \geq 0\) and \(x \geq 0\), it holds

\[\text{Prob}\{A(s, t) - \alpha(t - s) > x\} \leq f(x)\] (5)

**Definition 2:**

The virtual-backlog-centric model (v.b.c)

A flow \(A(t)\) is said to have a virtual-backlog-centric stochastic arrival curve \(\alpha \in \mathcal{F}\) with bounding function \(f \in \mathcal{F}\), denoted by:

\[A \sim \text{v.b.c} < f, \alpha >,\]

if for all \(t \geq 0\) and \(x \geq 0\), it holds

\[P[\sup_{s \leq t} A(s, t) - \alpha(t - s)] > x \leq f(x)\] (6)

**Definition 3:**

The max-virtual-backlog-centric model (m.b.c)

A flow \(A(t)\) is said to have a maximum-virtual-backlog-centric stochastic arrival curve \(\alpha \in \mathcal{F}\) with bounding function \(f \in \mathcal{F}\), denoted by \(A \sim \text{m.b.c} < f, \alpha >,\)

if for all \(t \geq 0\) and \(x \geq 0\), it holds

\[\text{Prob}\{\sup_{s \leq u} \sup_{u \leq t} [A(s, t) - \alpha(t - s)] > x\} \leq f(x)\] (7)

**Definition 4:**

The weak stochastic model (w.s)

A server is said to provide a flow \(A(t)\) with a weak stochastic service curve \(\beta \in \mathcal{F}\) with bounding function \(g \in \mathcal{F}\), denoted by \(S \sim \text{w.s} < g, \beta >,\)

if for all \(t \geq 0\) and \(x \geq 0\), it holds
**Definition 5:**

The stochastic service curve model (s.s.c)

A server is said to provide a flow $A(t)$ with a stochastic service curve $\beta \in \mathcal{F}$ with bounding function $g \in \mathcal{F}$, denoted by $S \sim sc < g, \beta >$, if for all $t \geq 0$ and all $x \geq 0$, it holds

$$\text{Prob}\left\{ \sup_{t \leq t} [A \otimes \beta(s) - A'(s)] > x \right\} \leq g(x)$$

**Definition 6:**

The strict stochastic service curve model (s.s.s.c)

A server is said to provide a strict stochastic service curve $\beta \in \mathcal{F}$ with bounding function $g \in \mathcal{F}$, denoted by $S \sim ssc < g, \beta >$, if during any period $(s, t)$ the amount of service $S(s, t)$ provided by the server satisfies

$$\text{Prob}(S(s, t) < \beta(t - s) - x) \leq g(x)$$

From these definitions, the properties of stochastic network calculus, including the stochastic backlog bound and stochastic delay bound is provided. It has been proved that $(\mathcal{F}, \wedge, \otimes)$ is a complete dioid, which is defined to have all the properties listed in Lemma 1.

**Lemma 1:**

$(\mathcal{F}, \wedge, \otimes)$ is a complete dioid having properties:

(i) Closure property: $\forall f, g \in \mathcal{F}, f \wedge g \in \mathcal{F}$; $f \otimes g \in \mathcal{F}$

(ii) Associativity: $\forall f, g \in \mathcal{F}, (f \wedge g) \wedge h = f \wedge (g \wedge h)$;

(f$\otimes$g)$\otimes$h = f$\otimes$(g$\otimes$h)$

(iii) Commutativity: $\forall f, g \in \mathcal{F}, f \wedge g = g \wedge f$; $f \otimes g = g \otimes f$

(iv) Distributivity: $\forall f, g \in \mathcal{F}, (f \wedge (g \otimes h)) = (f \otimes h) \wedge (g \otimes h)$

(v) Zero element: $\forall f \in \mathcal{F}, f \wedge \in = f$.

(vi) Absorbing zero element: $\forall f \in \mathcal{F}, f \otimes \in = \in \otimes f = \in$

(vii) Identity Element: $\forall f \in \mathcal{F}, f \otimes \in = \in \otimes f = f$

(viii) Idempotency of addition: $\forall f \in \mathcal{F}, f \wedge f = f$

In addition we have following properties:

**Lemma 2:**

$\forall f_1, f_2, g_1, g_2 \in \mathcal{F}$,

(ix) Comparison: $f_1 \wedge f_2 \leq f_1 \vee f_2 \leq f_1 \otimes f_2$

(x) Monotonicity:

If $f_1 \leq g_1$ and $f_2 \leq g_2$, then $f_1 \otimes f_2 \leq g_1 \otimes g_2$; $f_1 \wedge f_2 \leq g_1 \wedge g_2$; $f_1 \vee f_2 \leq g_1 \vee g_2$;

**Definition 7:**

In an acoustic network system, duration is termed as a loss period of it begins, when the server is full and the arrival rate is higher than the service rate and it results in the loss. If $A_{pk}(s, t)$ is a loss period, then the amount of loss during the time $(s, t)$, then the loss bound is expressed as,

$$P(L(s, t) > x) = P\left\{ A_{pk}(s, t) - D_{pk}(s, t) > x \right\}$$

With the above definitions, various properties of stochastic network calculus, including the stochastic backlog bound and the stochastic delay bound have been proved.

**Modeling Gilbert Elliot Channel For Underwater Acoustic Networks:**

Research on SNC [13] provides insights into stochastic service guarantees of packet networks for acoustic network applications. In the concept of Stochastic Service Curve as a probabilistic bound on the service received by an aggregation of flows or a single flow is represented.

**D. Acoustic Channel Model:**

Acoustic Gilbert Elliot Channel fading model is the simplest and fundamental channel model with its memory [14]. The acoustic Gilbert-Elliott Channel model is used to express the binary channel model in the
A two state Markov Chain is the fundamental feature of Gilbert-Elliot Channel Model and it is represented in Fig 1. The binary states 0 and 1 are used to represent the acoustic channel model in the packet level. 0 represents the acoustic packet loss and 1 represents the acoustic packet received in the acoustic receiver side. This shows whether the acoustic transmission channel is good or bad.

The moment generating function of two states Markov Chain is represented as follows. Assume a continuous time stationary process \( X(t) \) at time \( t \). The continuous time Markov Chain states are represented as \( S_0 \) and \( S_1 \). The transition rate between the state \( S_0 \) and \( S_1 \) is represented as \( P_b \) and the transition rate from states \( S_1 \) and \( S_0 \) is represented as \( P_g \). The average generator matrix \( F_x \) for Markov Chain function is given as,

\[
F_x = \begin{pmatrix} -P_b & P_b \\ P_g & -P_g \end{pmatrix}
\]  

(9)

The continuous time stationary process \( X(t) \) with the support of homogenous Markov Chain with generator matrix \( F_x \), the corresponding Moment generating function is from [16]

\[
M_x(0, t) \leq e^{\theta \rho(0)t}
\]  

(10)

Where \( \theta > 0, t \geq 0 \) and

\[
\rho = \frac{1}{2\theta} \left( \sqrt{(P_b - P_g + R)^2 + 4P_bP_g - P_b - P_g + R\theta} \right)
\]  

(11)

\( R \) represents the workload processed with rate. The acoustic Gilbert- Elliot Channel is represented as 0 and 1 or ON/OFF states. A continuous time ON/OFF data source is used to represent the acoustic channel model arrivals from bursty traffic sources. These binary states can be modeled to a two state Markov-Modulated source. The binary ON state represents the data generation at the rate \( \rho \) and the OFF state represents the acoustic channel is not transmitting any packet. So the states \( S_0 \) and \( S_1 \) can be replaces with ON/OFF States. The transition rate from ON to OFF is denoted as \( P_{ba} \) and the transition rate from OFF to ON is denoted as \( P_{ga} \). The generator matrix \( F_A \) in Markov Chain for the ON/OFF traffic source models is expressed from [17],

\[
F_A = \begin{pmatrix} -P_{ba} & P_{ba} \\ P_{ga} & -P_{ga} \end{pmatrix}
\]  

(12)

The elements of the steady state vector \( \pi_A = [\pi_{on}, \pi_{off}] \) are

\[
\pi_{on} = \frac{P_{ba}}{P_{ba} + P_{ga}}
\]

\[
\pi_{off} = \frac{P_{ga}}{P_{ba} + P_{ga}}
\]

The average traffic arrival rate is expressed as,

\[
\lambda = \pi_{on} R
\]  

(13)

The burstiness is defined as follows,
Let \( X(t) \) be the input and \( Y(t) \) be the output of the system with time instant at \( t \). The received acoustic channel fading is \( h(t) \). The total received signal is expressed as follows [18]

\[
Y(t) = h(t)X(t) + v(t)
\]

Where, \( v(t) \) represents the additive white Gaussian Noise with zero mean and sample variance. The fading component \( h(t) \) is considered to be zero-mean proper complex Gaussian process with zero mean and unit sample variance. When we channel envelop \( |h(t)| \) is above the threshold level, the acoustic channel is in good state and if the channel envelop is below the threshold level, the acoustic channel is in bad state. This channel is quantized as Rayleigh distribution channel and the states \( S_0, S_1 \) can be replaced with markov chain good and bad channel states. The acoustic state channel depends on transmission rate \( R \) chosen by the transmitter and the acoustic channel capacity of the acoustic underwater sensor networks is

\[
C(t) = W \log_2 \left( 1 + \frac{P|h(t)|^2}{N_0W} \right)
\]

Where \( P \) represents the power of the signal and \( W \) is the channel bandwidth. When the Gilbert-Elliot channel is in good state, the threshold \( \eta \) is expressed as,

\[
\eta = \sqrt{\frac{N_0W}{P} \left( \frac{R}{2W} - 1 \right)}
\]

And the maximum throughput under these assumptions are given as,

\[
RPr(|h(t)| > \eta) = Re^{-\eta^2}
\]

Performance Analysis on bounds:

Underwater wireless communication fading is implemented using SNC in [19][20][21][22]. In this section, the delay-constrained analysis is explained. Let the service of the channel be an independent stationary random process given by the cumulative process \( S(s,t) \). For all real \( \theta \), the corresponding moment generating function is denoted as \( M_s(-\theta, t) \). The departure process \( D(0,t) \) in the acoustic wireless channel with a varying server capacity is,

\[
D(0,t) \geq \inf_{s \in \mathbb{R}} \{A(0,s) + S(s,t)\}
\]

For the binary states Markov Chain continuous model with states good and bad, we have for \( \theta > 0, t \geq 0 \) and the delay constrained bound throughput \( \lambda_d \) of the acoustic channel under the delay guarantee is given as,

\[
\lambda_d = \max \{l | d^x \lambda, B \leq d \theta \}
\]

Where \( d^x \lambda, B \) assuming FIFO Scheduling and the stochastic bound on the delay can be obtained as follows.

\[
d(t) = \inf \{ \tau \geq 0 : A(0,t) \leq D(0, t + \tau) \}
\]

This employs for any \( \tau \geq 0 \), if \( d(t) > \tau \), there must be \( A(0,t) > D(0, t + \tau) \). The event \( d(t) > \tau \) implies the event \( \{A(0,t) > D(0, t + \tau)\} \) and it can be rewritten as,

\[
Pr\{d(t) > \tau\} \leq Pr\{A(0,t) > D(0, t + \tau)\}
\]

When rearrange equations, we have

\[
Pr\{d(t) > \tau\} \leq Pr\{A(0,t) > D(0, t + \tau)\} = Pr\{A(0,t) - D(0, t + \tau) > 0\} \leq Pr\{\sup_{s \in \mathbb{R}} \{A(s,t) - S(s,t + \tau)\} > 0\}
\]
\[
Pr(d(t) > \tau) \leq Pr \left\{ \sup_{0 \leq s \leq t} (A(s,t) - S(s,t + \tau)) > 0 \right\}
\leq E \left\{ e^{\theta \sup_{0 \leq s \leq t} (A(s,t) - S(s,t + \tau))} \right\}
\leq \sum_{s=0}^{\infty} E \left\{ e^{\theta(A(0,s) - \theta S(0,s + \tau))} \right\}
\leq \sum_{s=0}^{\infty} M_A(\theta, s - \tau) M_s(\theta, s)
\] (24)

In the above equation, when the right hand side is equal to \(\varepsilon\) and taking the natural log \(\ln\), the delay bound for the acoustic channel is expressed as,

\[
d^{\varepsilon, B} = \inf_{r>0} \left\{ \inf_{r>0} \left[ r: \frac{1}{\theta} (\ln \sum_{s=0}^{\infty} M_A(0,s - \tau) M_s(0,s) - \ln \varepsilon) \leq 0 \right] \right\}
\] (25)

\textbf{Simulation and Performance Evaluation:}

In this section, we present the performance evaluation of the derived mathematical models using simulations. In order to validate the tightness of the bound, we have simulated using the well-known commercial network simulation software tool OPNET, and compared the results of the simulation with their respective analytical results. The simulation parameters used are mentioned in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Simulation Parameters</th>
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<tbody>
<tr>
<td>Channel Bandwidth</td>
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<tr>
<td>Transmit Power</td>
</tr>
<tr>
<td>Noise Power Spectral Density</td>
</tr>
<tr>
<td>Carrier Frequency</td>
</tr>
<tr>
<td>Node Count</td>
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<tr>
<td>Delay</td>
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<td>Simulation Time</td>
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<tr>
<td>Transmission Time</td>
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<tr>
<td>Transmission Range</td>
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<td>Packet Size</td>
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A simulation setup for analyzing the effects of Gilbert-Elliot fading in an underwater acoustic network is deployed using transmitter and receiver nodes.

Fig. 2 shows the OPNET simulation environment with fourteen nodes. The two intermediate relay nodes monitor the data arrival rate and the service rate among the nodes. OPNET by default supports wireless radio signal communication. For each pair of transmit and receive channels, the wireless transmission processing can be described by a series of sub-transmission blocks. These transmission blocks are parameters whose calculations are related to the wireless link. Specifically, for each pair of transmitter and receiver, OPNET builds
the pipeline transmission phases. When a packet is ready to transmit, the original packet will always be copied at least once. The physical layer is modeling the wireless receiver and the transmitter module. It is divided into 14 pipeline attributes. In order to model an acoustic channel, there is a need to modify the coding’s that supports acoustic channel communication. The radio transmitter node attributes and the radio receiver attributes are modified to corresponding acoustic transmitter and acoustic receiver nodes. In order to simulate the acoustic link, modifications should be done in the following stages of the OPNET Transceiver pipeline:

1. Propagation Delay stage
2. Received Power stage
3. Bit error stage
4. Background Noise stage
5. Signal to Noise ratio stage and Channel Match Stage

In the numerical results, we consider the Gilbert-Elliot Channel parameters mentioned in Table 1.

Fig. 3: Violation Probability vs. Delay Bound

Fig 3 shows the relationship between the delay bound and the violation probability. Simulation test case runs for 20 minutes and the delay violation probability tightness in our simulation verifies the tightness of the bound. Fig 4 shows the relationship between the throughput and the delay for a single node. The delay-constrained throughput is calculated based on equation from equation (19) to equation (25). The infinite sum in the delay bound formula is given in equation (25). The infinite sum is calculated for the first 1000 units of time and delay bound violation probability. Fig 5 shows the relationship between the delay guarantees on the delay-constrained throughput for different values of the delay violation probabilities.

Fig. 4: Throughput vs Delay

The graph shows that a stringent service guarantee given by a lower violation probabilities will obviously results in the decrease in the throughput.
The throughput will increase steadily after certain point. This is because the arrival rate approaches the system capacity limited mentioned in the numerical result equation (23) and (24). In Fig 6, the relationship between the effect of burstiness and the throughput is given. The graph shows that there is an exponential decay of delay-constrained throughput with burstiness. Our results suggest that conventional performance measures are not well suited to describe the throughput limits of the communication networks with delay sensitive sources. As we have modeled the delay constrained throughput with delay violation probabilities to measure the traffic carrying capacity of the network.

**Conclusion and Future Work:**

In this research work, we have constructed both the analytical and its simulations, to understand and model the Gilbert Elliot Channel fading effects of the acoustic channel using stochastic network calculus. The analysis method is validated through respective simulations with delay-constrained throughput. The numerical results impact the delay guarantee, traffic burstiness on the delay-constrained throughput.

![Fig. 5: Delay Guarantee vs Throughput](image)

![Fig. 6: Burstiness vs. Throughput](image)

**REFERENCES**

