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Queueing-Theoretic Performance Analysis of High-Speed Communication Networks with Malicious Traffic, Multi-Phase Sleep Policies, and Server Failures

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Abstract
A modern 4G/5G Computer Network (CN) operates as a group of interconnected autonomous Nodes responsible for handling distributed information tasks. When subjected to cyber-attacks, Such networks may experience costly service interruptions. In the present study, the CN is represented through a queueing framework that incorporates server failures and several sleep states, which depend on the category of the arriving data packets namely Regular (Rp), Spoofed (Sp) and ping-of-Death (Pod) packets. The arrival of any packet forces the system to exit its sleep mode and restore normal server activity. To investigate the behaviour of the system, the queue-length PGF at an arbitrary time is derived through the supplementary variable technique. This functional form enables the computation of several key performance measures, such as the mean number of packets in the system, the average waiting time per packet, the expected length of busy intervals, and overall operational cost. These metrics are further illustrated through suitable numerical examples.

Keywords: DOS attack; Different classes of arrivals;4G/5G; Batch arrival; Multiple sleeps; Server breakdown; Supplementary variable technique.

1. Introduction

Enterprise networks must maintain adequate bandwidth to reliably sustain essential applications and organizational operations. However, several conditions can hinder the effective utilization of this bandwidth. Bandwidth represents the maximum data-carrying capacity of a communication link, whereas the actual data transfer rate known as throughput indicates how fast information is delivered. Even with careful bandwidth estimation and capacity planning by network administrators, unexpected factors can arise that consume excess bandwidth and degrade traffic performance. Among these challenges, Denial-of-Service (DoS) attacks pose a particularly serious risk to corporate networks. In such environments, a network packet serves as the fundamental unit of date exchanged within packet-switched communication systems. A packet is composed of two essential parts: the payload, which contains the actual user data, and the control information, which enables its reliable transmission. The control information typically includes the source and destination addresses, mechanisms for error detection, and sequencing details that ensure the packet is correctly ordered and delivered across the network. Usually, packet headers and trailers contain control information. Internet protocol IP packet spoofing refers to the deliberate creation of Internet protocol packets that carry a falsified source address, enabling an attacker to conceal their identity or impersonate another device on the network. When an adversary exploits this technique to masquerade as a legitimate user or system and sends malformed or excessive packets intended to overload or crash a server, the attack is commonly known as a ping of Death. System downtime caused by such malicious actions can severely disrupt business operations. Unexpected failures of critical applications or network services not only interrupt workflow but may also lead to substantial data loss and significant financial damage. In extreme cases, prolonged or repeated indicents of downtime can threaten the survival of the organization itself. When these disruptions steam from intentional cyberattacks, the associated financial and operational consequences escalate rapidly, often reaching levels that are devastating for the business.

Haridass and Arumuganathan (2012) investigated the steady-state characteristics of an M_x/G/1queueing system incorporating multiple vacations and setup times. Their model employs an N-policy framework along with vacation mechanism, and it is used to study the operational behaviour of the Discontinuous Reception (DRX) technique in LTE-A networks. Kandaiyan, Indira and S.P Niranjan (2016) provided a comprehensive review of research on bulk arrival queues featuring vacation policies. Similarly, Li Jihong and Naishuo Tian (2011) aimed the equip practitioners and researchers with the necessary theoretical foundations to model traffic processes and to derive performance metrics essential for optimizing queueing systems. Sivakami Sundari et al. (2020) analysed service facility productivity and evaluated key waiting-line performance indicators-including average queue length

and waiting time which serve as inputs for planning and designing service installations. IN another line of work, Umar and Dhabilya highlighted several critical attributes of their proposed method, such as indivisible authentication, rapid verification, and low communication and storage overhead.Fais, Lettieri and Procissi (2022) focused on the use of SPSs within multicore environments, proposing a unified approach that offers both high performance and expressive capability. In this work, we propose a batch-arrival queueing model with three packet classes (regular, spoofed and ping of death), multiple sleep phases, and server breakdowns. The model explicitly incorporates batch arrivals, slow service under malicious traffic, breakdowns followed by repair and repeated vacation phases when the system is empty.

The main contributions of this paper are:

- A rigorous stochastic model incorporating batch arrivals and multiple sleep phases.
- A mathematically consistent derivation of the steady state queue size distribution
- A stability condition obtained from positive recurrence arguments.

Numerical illustrations demonstrating the effect of malicious traffic on congestion and cost.

2. Model description

This work investigates a single-server queueing system with bulk arrivals in which the server is subject to both breakdowns and vacation periods. Packets of three distinct classes enter the system in batches, following independent poisson inputs streams with respective rates
δ_1, δ_2, δ_3. The server handles packets individually and begins service whenever the system contains atleast one packet.

Regular Packets:

Regular packets correspond to legitimate date traffic generated by authorized users or normal network applications. These packets conform to standard communication protocols and are processed by the server under normal operating conditions.

Spoofed packets:

Spoofed packets are malicious packets in which the source IP address is intentionally falsified by an attacker. Such packets are used to disguise their true origin and to mimic legitimate traffic, thereby increasing the load on the system and potentially degrading its performance.

Ping-of-Death packets:

Ping-of-Death packets are malformed or oversized ICMP packets transmitted with the objective of exploiting vulnerabilities in the target system. These packets may cause buffer overflow, abnormal system behavior, or server failure, resulting in service interruption.

Batch Size:

Batch size refers to the number of packets that arrive simultaneously in a single arrival event. Let α denote the batch size random variable; then $P(\alpha = k)$represents the probability that a batch contains k packets, and $E(\alpha)$ denotes the mean batch size.

Multiple sleep:

Multiple sleep (also called multiple vacation) refers to a server operating policy in which the server, after completing a service and finding the system empty, enters a sleep (vacation) state. If, upon returning from sleep, the server still finds no packets waiting in the system, it immediately takes another sleep period. This process is repeated until at least one packet is present in the system, at which time the server resumes service.

If a breakdown occurs whether during the processing of a spoofed packet under reduced service capacity or while handling a ping-of-death packet with normal or degraded service the server is immediately transferred to a repair facility, where recovery commences without any waiting time. When the server detects that the queue length has fallen below a required threshold, it starts a vacation. After completing a vacation, the server resumes service provided the queue is non-empty.

Description	symbol
Regular packet arrival rate	δ_1
Spoofed packet arrival rate	δ_2
Ping of death packet arrival rate	δ_3
Regular service time random variable	S_1
Slow service time random variable	S_2
Batch size random variable	α

Repair time random variable	R
Vacation time random variable	V
Probability generating function (PGF) of queue size	G(x)
Mean batch size	E (α)

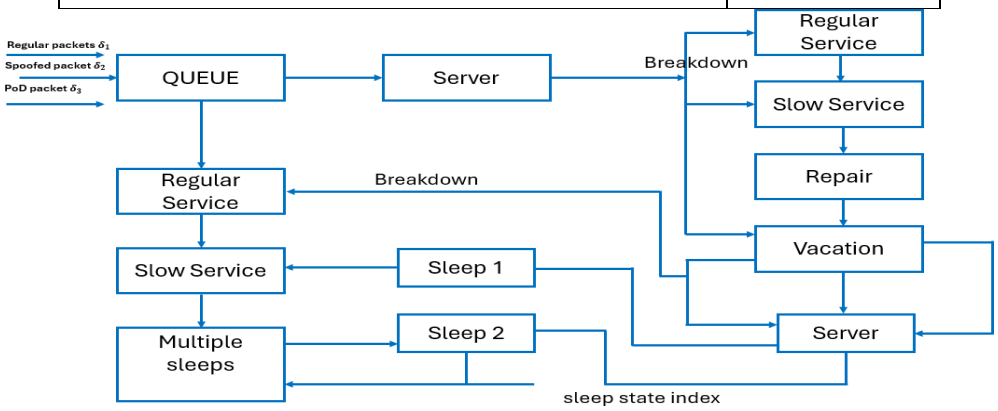


Figure 1: Schematic representation of proposed model.

3. Mathematical model

The system receives three independent Poisson arrival streams corresponding to regular, spoofed and ping-of-death packets with rates δ_1, δ_2, and δ_3, respectively.

Arrivals occur in batches according to a compound Poisson process. Let αdenote the batch size with distribution $\{\alpha_k\}$and mean $E[\alpha]$. Thus, the effective arrival rate is $\delta_i E[\alpha]$, $i = 1,2,3$.

Let S_1 and S_2 denote the regular and slow service times, whose distribution functions are $S_1(\alpha)$and $S_2(\alpha)$,densities $s_1(\alpha)$and $s_2(\alpha)$, and Laplace–Stieltjes transforms (LSTs) $\tilde{S}_1(\theta)$and $\tilde{S}_2(\theta)$. Following a server breakdown, the repair time is denoted by the random variable R, With cumulative distribution function $R(\alpha)$, density $r(\alpha)$, and LST $\tilde{R}(\theta)$. The vacation time of the server is characterized by the random variable V , with distribution funct-

ion function $V(\alpha)$, density $v(\alpha)$, and LST $\tilde{V}(\theta)$.

Let $M(h)$ denote the state of the server at time h, defined as

0, server is providing regular service,

1, server is providing slow service,

$M(h) = \{$

2, server is under repair,

3, server is on vacation.

Since the service, repair, and vacation times follow general distributions, the queueing system is naon-markovian in its original formulation. By introducing supplementary variables representing the remaining service, repair and vacation times, the system can be equivalently reformulated as a continuous-time Markov process on a countable state space. This augmented Markov process forms the basis for the steady-state and stability analysis carried out in sequel.

$G_{0,j}(\alpha, h) = Pr\{M(h) = 0, Nq(h) = j\ \alpha \le T_1^0(h) \le \alpha + dh\ \}\ j > 0$ represents the likelihood that, at time h, the server is operating in the regular-service mode with exactly

j packets waiting, and that the residual regular-service time lies in the interval $[\alpha, \alpha + d\alpha]$.

$G_{1,j}(\alpha, h) = Pr\{M(h) = 1, Nq(h) = j, \alpha \le T_2^0(h) \le \alpha + dh\ \}\ j > 0$ represents in which the server is performing slow service at time h, the queue holds j packets, and the remaining slow service time falls within $[\alpha, \alpha + d\alpha]$.

$G_{2,j}(\alpha, h) = Pr\{M(h) = 2\ , Nq(h) = j, \alpha \le R^0(h) \le \alpha + dh\}\ \ j > 0$ is the probability that the server is undergoing repair while j packets are present in the queue, with the residual repair time lying in the same small interval $[\alpha, \alpha + d\alpha]$.

$H_{l,j}(\alpha, h) = Pr\{M(h) = 3, Nq(h) = j\ , \alpha \le V^0(h) \le \alpha + dh\}\ j = 0\ , l \ge 1$denotes the probability that, at time h, the server is in its l-th vacation, the system is empty, and the remaining vacation time falls between $[\alpha, \alpha + d\alpha]$.

4. Steady State Queue Size Distribution

The aforementioned notation and probability distributions form the basis for deriving the steady-state queue length distribution. By applying the supplementary variable approach, the following system of equations is established.

$$G_{0,j}(\alpha-\Delta h,\alpha+\Delta h) = G_{0,j}(\alpha,h)(1-\delta\Delta h)+\delta_1\sum_{k=1}^{j}\alpha_k\, G_{0,j-k}(\alpha,h)\Delta h + \sum_{l=1}^{\infty} H_{l,j}(0,h)\,\Delta h\ ,\ j\geq 0 \quad (1)$$

$$G_{1,j}(\alpha-\Delta h,h+\Delta h) = G_{1,j}(\alpha,h)(1-\delta\Delta h)+\delta_1\sum_{k=1}^{j}\alpha_k\, G_{1,j-k}(\alpha,h)\Delta h + \delta_2\left[\int_0^{\infty} G_{0,j}(\alpha,h)d\alpha\right] s_2(\alpha)\Delta h \quad (2)$$

$$G_{2,j}(\alpha-\Delta h,\alpha+\Delta h) = G_{2,j}(\alpha,h)(1-\delta\Delta h)+\delta_1(1-\delta_{0,j})\sum_{k=1}^{j}\alpha_k\, G_{2,j-k}(\alpha,h)\Delta h + \delta_3\left[\int_0^{\infty} G_{1,j}(\alpha,h)d\alpha\right] r(\alpha) + (\delta_2+\delta_3)\left[\int_0^{\infty} G_{1,j}(\alpha,h)d\alpha\right] r(\alpha)\Delta h + \sum_{l=1}^{\infty} H_{l,j}(0,h)\,\Delta h,\ j\geq 0$$

$$\text{where } \epsilon_{0,j}=\begin{cases}0 & j\neq 0\\ 1 & j=0\end{cases} \quad (3)$$

$$H_{1,0}(\alpha-\Delta h,h+\Delta h) = H_{1,0}(\alpha,h)(1-\delta\Delta h)+G_{0,0}(0,h)v(\alpha)\Delta h+G_{2,0}(0,h)v(\alpha)\Delta h \quad (4)$$

$$H_{l,j}(\alpha-\Delta h,h+\Delta h) = H_{l,j}(\alpha,h)(1-\delta\Delta h)+H_{l-1,j}(\alpha,h)\Delta h \quad (5)$$

$$H_{l,0}(\alpha-\Delta h,h+\Delta h) = H_{l,0}(\alpha,h)(1-\delta\Delta h)+H_{l-1,0}(\alpha,h)\Delta h \quad (6)$$

Here, $\delta=\delta_1+\delta_2+\delta_3$ denotes the total arrival rate. The above system represents the steady-state balance equations of the augmented Markov process and is valid only Under the positive recurrence condition $\rho<1$.
From the above equation the steady size queue size equations are obtained as follows:

$$-\frac{d}{d\alpha}G_{0,j}(\alpha) = -\delta G_{0,j}(\alpha)+\delta_1 G_{0,j-1}(\alpha)+\sum_{l=1}^{\infty} H_{l,j}(\alpha,0) \quad i\geq 0 \quad (7)$$

$$-\frac{d}{d\alpha}G_{1,j} = -\delta G_{1,j}+\delta_2\left[\int_0^{\alpha} G_{1,i}(\alpha)d\alpha\right]+\delta_1(1-\epsilon_{0,i})G_{1,i-1}$$

$$-\frac{d}{d\alpha}G_{2,j}(\alpha) = -\delta_1 G_{2,j}(\alpha)+\delta_3\left[\int_0^{\alpha} G_{1,j}(\alpha)d\alpha\right] r(\alpha)+\delta_1(1-\epsilon_{0,j})G_{2,j-1}(\alpha) + \delta_2+\delta_3\left[\int_0^{\alpha} G_{2,j}(\alpha)d\alpha\right] r(\alpha)+\sum_{l=1}^{} H_{l,j}$$

$$-\frac{d}{d\alpha}H_{1,0}(\alpha) = -\delta H_{10}(\alpha)+G_{0,0}(\alpha)v(\alpha)+G_{2,0}(\alpha)v(\alpha) \quad l=1,j=0 \quad (10)$$

$$-\frac{d}{d\alpha}H_{l,0}(\alpha) = -\delta H_{l,0}(\alpha)+H_{l-1,0}(\alpha)\ l\geq 1,j=0 \quad (11)$$

$$-\frac{d}{d\alpha}H_{l,j}(\alpha) = -\delta H_{l,j}(\alpha)+\delta H_{l,j-1}(\alpha) \quad l\geq 1,\ \ j\geq 0 \quad (12)$$

The Laplace Steiljes transform of $P_{i,j}(\alpha)$ i =1, 2, 3 are defined as

$$\text{LST}[G_{i,j}(\alpha)] = \tilde{G}_{i,y}(\theta) = \int_0^{\infty} e^{-\alpha\theta} G_{i,j}(\alpha)\, d\alpha$$

$$\text{LST}[H_{l,j}(\alpha)] = H_{i,y}(\theta) = \int_0^{\infty} e^{-\alpha\theta} H_{lj}((\alpha)\, d\alpha$$

Taking LST of equations 1 to 6 we have

$$\varphi\tilde{G}_{0,y}(\varphi) - G_{0,j}(0) = \tilde{G}_{0,y}(\varphi) - \delta\, G_{1\ 0,j-1}(\varphi) - \sum_{l=1}^{\infty} H_{l,j}(\alpha, 0)\ l \geq 1, j \geq 0 \qquad (13)$$

$$\varphi\tilde{G}_{1,y}(\varphi) - G_{1,j}(0) = \delta\tilde{G}_{1,y}(\varphi) - \delta_1 G_{1,j}(\varphi)S_2(\varphi) - \delta_1\ (1 - \delta_{0,j})\ G_{1,j}(\theta)\ \ j \geq 0 \qquad (14)$$

$$\varphi\tilde{P}_{2,y}(\varphi) - G_{2,j}(0) = \tilde{G}_{2,y}(\varphi) - \delta_3 G_{2,j}(\varphi)R(\varphi) - \delta_2\ (1 - \epsilon_{0,j})\ G_{2,j-1}(\varphi)$$

$$\varphi H_{l,y}(\varphi) - H_{l,j}(0) = H_{l,y}(\varphi) - (\delta)\ (\tilde{H}_{,y-1}(\varphi)) \qquad (16)$$

$$\varphi\tilde{H}_{1,0}(\varphi) - H_{1,0}(0) = \delta\tilde{H}_{10}(\varphi) - G_{0,0}(0)V(\varphi) - G_{2,0}(0)V(\varphi) \qquad (17)$$

$$\varphi\tilde{H}_{l,0}(\varphi) - H_{l0}(0) = \tilde{H}_{l,0}(\varphi) - (H_{l0})V(\varphi) \qquad (18)$$

5. Probability Generating Function

To derive the probability generating function (PGF) for the system size at an arbitrary time point, the following generating functions are introduced.

$$\tilde{G}_{0,y}(x) = \sum_0^{\infty} G_{0,j}(\varphi)x^j; \qquad G_0(x) = \sum_0^{\infty} G_{0,j}(0)x^j$$

$$\tilde{G}_{1,y}(x, \varphi) = \sum_0^{\infty} G_{1,j}(\varphi)x^j \quad ; \qquad G_1(x) = \sum_0^{\infty} G_{1,j}(0)x^j$$

$$\tilde{G}_{2,y}(x, \varphi) = \sum_0^{\infty} G_{2,j}(\varphi)x^j; \qquad G_2(x) = \sum_0^{\infty} G_{2,j}(0)x^j$$

$$\tilde{H}_{1,y}(x, \varphi)) = \sum_0^{\infty} H_{1,j}(\varphi)x^j; \qquad H_{1,j}(x) = \sum_0^{\infty} H_{1,j}(0)x^j$$

Substituting the equation (5) to (8) by x^n and taking summation from n=0 to $\propto$
Then

$$(\varphi - (\delta + \delta_1 x))\tilde{G}_0(x, \theta) = G_0(x, 0) - \delta_1\tilde{G}_0(x, 0)S(\theta) + H_{1,j}(x, 0) \qquad (19)$$

$$(\varphi - (\delta - \delta_1 x))G_1(x, \theta) = G_1(x, 0) - G_1(x, 0)S_2(\theta) \qquad (20)$$

$$(\varphi - (\delta_1 + \delta_1 x))G_2(x, 0) = G_2(x, 0) - \delta_3\tilde{G}_1(x, 0) + (\delta_2 + \delta_3)G_2(x, 0)R(\theta) + H_{l,j}(x, 0) \qquad (21)$$

$$(\varphi - (\delta + \delta x))\tilde{H}_l(x, \theta) = H_l(x, 0) - (G_{0,0} + G_{2,0})V(\varphi) \qquad (22)$$

$$(\varphi - (\delta + \delta x))\tilde{H}_l(x, \varphi) = H_l(x, 0) - H_{l-1}(\varphi)V(\varphi) \qquad (23)$$

The probability generating function G (x) of number of customers in system is given by

$$G(x) = G_0(x) + G_1(x) + G_2(x) + \sum_{l=1}^{\infty} H_{l,j}(x, 0) \quad (24)$$

substituting $\varphi = \delta - \delta_1 x$ *in* (19) *we have*

$$G_0(x) = \delta_1 G_0(x) S(\delta - \delta_1 x) + H_l(x, 0) \quad (25)$$

$$G_1(x) = \delta_2 G_1(x, 0) S_2(\delta - \delta_1 x) \quad (26)$$

substituting $\varphi = \delta_1 - \delta_1 x$ *in* (20) *we have*

$$G_2(x) = \delta_3 G_2(x, 0) + (\delta_3 + \delta_2) G_2(x, 0) R(\delta_1 - \delta_1 x) + H_l(x, 0) \quad (27)$$

substituting $\varphi = \delta - \delta x$ in (22) and (23) we get

$$H_l(x, 0) = (G_{0,0} + G_{2,0}) V(\delta - \delta x)$$

$$H_l(x, 0) = V(\delta - \delta x) \quad (28)$$

Substituting equation (28), eqn (22) and (23)

$$\tilde{H}_1(x, 0) = \frac{(G_{0,0} + G_{2,0}) \tilde{V}((\delta - \delta x) - 1)}{(-\delta + \delta x)} \quad (29)$$

$$\tilde{H}_l(x, 0) = \frac{H_{l,0}(0) \tilde{V}((\delta - \delta x) - 1)}{(-\delta + \delta x)} \quad (30)$$

From equation (23) and (24) we have

$$\sum_{l=1}^{\infty} \tilde{H}_l(x, 0) = \frac{(G_{0,0} + G_{2,0}) \tilde{V}((\delta - \delta x) - 1) + \sum_{l=1}^{\infty} H_{l,0}(0)}{(-\delta + \delta x)} \quad (31)$$

From equation (19) we have

$$G_0(x) = \frac{H_{l,0}(x) \tilde{V}((\delta - \delta x) - 1)}{\delta_1 S(\delta - \delta_1 x)) - 1} \quad (32)$$

Substituting

$G_0(x, 0), G_1(x, 0), G_2(x, 0), G_3(x, 0), H(x, 0)$ *from equation* 25,26,27,28

in 19,20,21,222 *respectively we have*

$$G_0(x, 0) = \frac{\delta_1 G_0(x) S((\delta - \delta_1 x) - 1) + H_{l,0}(x) V((\delta - \delta x) - 1)}{(-\delta + \delta_1 x)} \quad (33)$$

Theorem: 1

The probability generating function G (x) of number of packets in the queue is given as follows:

$$G(x) = \frac{(\delta_1 G_0(x)\,(\delta_2((S(\delta-\delta_1 x)-1) + H_{l,0}(x)V((\delta-\delta x)-1))}{(-\delta+\delta_1 x)} + \frac{\delta_3(\delta_1 G_0(x) + (\delta_2+\delta_3)S_2((\delta-\delta_1 x)-1)}{(-\delta+\delta_1 x)^2} + \frac{\delta_3(\delta_3 G_0(x) + (\delta_2+\delta_3)(\delta_2 G_0(x))(S((\delta-\delta_1 x)-1)(R(\delta-\delta_1 x)-1)) + H_{l,0}(x)V(\delta-\delta x)-1))}{(-\delta+\delta_1 x)(-\delta_1+\delta_1 x)}$$

Where $G_0(x)$ *is given by equation* (32)

6. Stability Condition

The stability of the system is examined using the probability generating function $G(x)$of the stationary queue size distribution. For the system to be stable, the mean queue length must be finite, which requires that
$G(1) = 1$and$G'(1) < \infty$.

From the expression of $G(x)$in equation (32), it is observed that the denominator terms contain factors of the form $(-\delta + \delta_1 x)$and $(-\delta_1 + \delta_1 x)$. Hence, for $G(x)$to be well defined in a neighborhood of $x = 1$, the effective traffic intensity must be less than unity.

Let αdenote the batch size random variable with mean $E(\alpha)$. Packets arrive in batches according to three independent Poisson streams corresponding to regular, spoofed, and ping-of-death packets with rates δ_1, δ_2, and δ_3, respectively. Therefore, the effective arrival rate of packets is

$$\delta = (\delta_1 + \delta_2 + \delta_3)E(\alpha).$$

Due to the presence of multiple service modes, repairs, and vacations, the effective mean service time is given by

$$E(S_{\text{eff}}) = \delta_1 E(S_1) + (\delta_2 + \delta_3)E(S_2) + \delta_3 E(R) + E(V),$$

where $E(S_1)$and $E(S_2)$denote the mean regular and slow service times, respectively, $E(R)$is the mean repair time, and $E(V)$is the mean vacation time.

Hence, the traffic intensity of the system is

$$\rho = (\delta_1 + \delta_2 + \delta_3)E(\alpha)\,E(S_{\text{eff}}).$$

The necessary and sufficient condition for the existence of the steady-state distribution is

$$\boxed{\rho < 1.}$$

7. Computational Aspects Of Unknown Constant

The unknown constant appearing in the expression for G(x) must be written in terms of known quantities. Since the system under consideration is an M/G/1 single-server queue, the generating function G(x) should contain only one unknown constant. However, the model produces two unknown constants. To resolve this and express the constant q_0 in terms of known quantities, the following theorem is used.

Theorem: 2

If β_n *is the probability of n customers arriving during a vacation then* $q_0 = \frac{\beta_0 p_0}{1-\beta_0}$ where $q_0 = \sum_{l=1}^{\infty} H_{l,0}(0)$ *and* $p_0 = p_0(0)$

Proof:

Using q_0 $H_{l,0}(0)$ *and* p_0 $= p_0(0)$ in equation (23), (24) simplifies to

$$= \sum_{l=1}^{\infty} H_{l,0}(0) \text{ and } p_0 = p_0(0) \text{ in equation (23), (24) simplifies to}$$

$$\sum_{l=1}^{\infty} H_l(x,0) = \sum_{i=1}^{\infty} \sum_{n-i}^{\infty} H_{l,n}(0)x^n$$

$$= (G_{0,0} + G_{2,0})V(\delta - \delta x) + \sum_{l=1}^{\infty} H_{l,0}(0)$$

$$= \sum_{n-0}^{\infty} \beta_n x^n (q_0 + p_0)$$

Equating the constant terms on both sides of the above equation, we have

$$q_0 = \beta_0(p_0 + q_0)$$

$$q_0 = \frac{\beta_0 p_0}{1 - \alpha_0}$$

Hence, the theorem has been proved.

8. Performance Characteristics

This section develops the key performance indicators associated with the proposed queueing framework. Specifically, it derives the steady-state probabilities corresponding to the server being idle, performing regular service, undergoing repair, operating in the slow service mode, or remaining on vacation. In addition, expressions for the expected queue length and the average waiting time encountered by incoming packets are obtained.

8. A. The Mean number of packets in the queue

The mean queue length is determined through the application of the probability generating function in equation (32) and $L_Q = \lim_{x \to 1} \frac{d}{dx} G(x)$, Since the expression for $G(x)$ is too large the numerical values of LQ are calculated using software mathematics.

$$L_Q = \frac{G_0(x)\,[\delta_1^2 \tilde{S}(\delta - \delta_1 - 1) + (\delta_2 + \delta_3)\tilde{S}_2(\delta - \delta_1 - 1)E(R) + E(V)(p_0 + q_0)}{\delta_1 \delta(-\delta + \delta_1^2)\tilde{S}((\delta - \delta_1) - 1)}$$

Where $G_0(x)$ *is given by equation* (32)

8. B. The Mean delay time in the queue

By applying Little's law, the average waiting time in the queue is derived W_Q

$$= E(W) = \frac{L_Q}{\delta_1}$$

8. C. Probability that the server is engaged in regular service

Let B_1 denote the busy- period random variable corresponding to the server operating in the regular service mode, and $P(B_1)$ represent the probability that the server is performing regular service at time h. By referring to equation (33) and taking limit as $x \to 1$, the probability associated with the server being in the regular service state is obtained as follows.

$$G_0(1,0) = P(B_1) = \frac{\delta_1 S(\delta - \delta_1 - 1) + E(V)(p_0 + q_0))}{(-\delta + \delta_1)\delta_1 S((\delta - \delta_1 x) - 1)} \qquad (39)$$

where $P_0(1)$ *is given by equation* (32).

8. D. Probability that the server is engaged in slow service

Let B_2 denote the busy-period random variable corresponding to the server operating under the slow service mode and let $P(B_2)$ represent the probability that the server is performing slow service at time h.by utilizing Equation (34) and taking the limit as $x \to 1$, the probability associated with the server being in the slow-service state is obtained as follows

$$G_1(1,0) = P(B_2) = \frac{\delta_3(\delta_2+\delta_3)S_2((\delta-\delta_1)-1)}{(-\delta+\delta_1)^2\ \delta_1 S\delta-\delta_1))-1} \quad (40)$$

Where $P_0(1)$ *is given by equation* (32)

8. E. Probability that the server is under repair

Let R be the busy period random variable when the server is under repair and P(**R**) be the probability that the server is under repair at time h. using the Equation (35) and applying $x \to 1$ we get the probability that the server is on vacation as follows:

$$G_2(1,0) = P(R) = \frac{\delta_3(\delta_1 G_0(1) + (\delta+\delta_3)(\delta_1 G_0(1))(S((\delta-\delta_1)-1)(E(R))+E(V)(p_0+ q_0)}{(-\delta+\delta_1 x)^2(-\delta+\delta_1 x)\delta_1 S((\delta - \delta_1 x))-1} \quad (41)$$

where $G_0(1)$ *is given by equation* (32).

8. F. Probability that the server is under vacation

Let V denote the vacation-time random variable, and let P(V) represent the probability that the server is in vacation state at time h. Using the equation (23) and (24) and applying $x \to 1$ we get the probability that the server is on vacation as follows:

$$P(V) = \frac{E(V)(p_0+ q_0)}{\delta_1 S((\delta-\delta_1)-1} \quad (42)$$

where $G_0(1)$ is given by equation (32).

8. G. Expected Length of Busy Period

Let B denote the busy-period random variable. Let H represent the residence time during which the server operates either in the regular service mode or in the slow service mode. Therefore, H=S1with probability 1- $\pi\beta$. and H= S1+ S2 with probability $\pi\beta$.

Another random variable J is defined as, 0, if the server finds less than 'one' customers after a residence time J is defined as 1, if the server finds at least 'one' customer after a residence time.

Now, the expected length of busy period E (B) is given by

$$E(B) = E(B/J=0)\,P(J=0) + E(B/J=1)\,P(J=1)$$

$$E(B) = \frac{E(S1)}{(1-\pi\beta)pn+rn} + \pi\beta E(S_2) \quad (43)$$

9. Special Cases

9. A. Particular Case

When $\delta_2 = \delta_3 = 0$and $\tilde{V}(\delta - \delta x) = 1$, all terms corresponding to spoofed and ping-of-death packets vanish and the model reduces to a classical batch-arrival system. Equation (32) simplifies to

$$G(x) = \frac{(1-\rho)(1-x)S(\delta-\delta_1 G_0(x))}{S(\delta-\delta\ G_1(x)) - x},$$

which coincides with the steady-state queue-size probability generating function of the $M^X/G/1$queue obtained by Goutam Choudhury (2007)

9. B. Special Cases

Although the proposed model permits the service time to follow any arbitrary probability distribution, practical implementations often require choosing a specific form. Therefore, in this section, it examines particular instances of the model by assuming that the service-time random variable follows either an Erlang distribution or a Hyper-exponential distribution.

Case (i) : M/EK/1 queuing with three classical of customers (Erlang service time both for regular service and slow service, multiple vacations subject to server breakdown and repair.

If the service times are assumed to be Erlang with probability density functions

$$s(\alpha) = \frac{(k_1 u_1)^{k_1} \alpha^{k_1-1} e^{-k_1 u_1 \alpha)}}{(k_1-1)!} where u_1, \alpha\ \alpha > 0$$

$, k_1$ *is a positive integer and* u_1 *is a parameter.*

$$s_2(\alpha) = \frac{(k_2 u2)^{k_2} \alpha^{k_2-1} e^{-k_2 u_2 \alpha)}}{(k_2-1)!} where u_2, \alpha > 0$$

$, k_2$ *is a positive integer and* u_1 *is a parameter.*

Then

$$S(\delta - \delta_1 x) = \left(\frac{u_1 k_1}{u_1 k_1 + \delta - \delta_1 z}\right)^{k1}, S_2(\delta - \delta_1 x) = \left(\frac{u_2 k_2}{u_2 k_2 + \delta - \delta_1 z}\right)^{k2} \quad (44)$$

Substituting for G (x) in equation (32) for $S(\delta - \delta_1 x)$ and $S_2(\delta - \delta_1 x)$ from equation (39)

$$G(x) = \frac{(\delta_1 G_0(x)\,(\delta_2((\frac{u_1 k_1}{u_1 k_1+\delta-\delta_1 z})^{k_1} + H_{l,0}(x) V(\delta-\delta x-1)))}{(-\delta+\delta_1 x)^2}$$

$$+ \frac{\delta_3(\delta_1 G_0(x) + (\delta_2+\delta_3)(\frac{u_2 k_2}{u_2 k_2+\delta-\delta_1 x})^{k_2}}{(-\delta+\delta_1 x)^2(-\delta_1+\delta_1 x)}$$

$$+ \frac{\delta_3(\delta_3 G_0(x) + (\delta_2+\delta_3)(\delta_2 G_0(x))(\frac{u_1 k_1}{u_1 k_1+\delta-\delta_1 z})^{k_1}(R(\delta-\delta_1 x)-1)) + H_{l,0}(x) V(\delta-\delta x)-1)}{(-\delta+\delta_1 x)^2(-\delta_1+\delta_1 x)}$$

$$\frac{(\delta\ G\ (x)(G\quad +G\quad)V((\delta-\delta x)-1)+(\delta\ G\ (x)\sum^{\infty}\ H\ \ (0)V(\delta-\delta x)-1)}{1\ \ 0\qquad 0,0\quad 2,0\qquad\qquad\qquad\qquad 1\ \ 0\qquad l=1\quad l,0}$$

$$\text{where } G_0(x) = \frac{H_{l,0}(0)V((\delta-\delta x)-1)^{(-\delta+\delta x)}}{\delta 1\left(\frac{u_1 k_1}{u_1 k_1+\delta-\delta_1 x}\right)^{k_1}} \qquad (45)$$

Case (ii): M/Hyper exponential/1 queuing with three classical of customers

$$s(\alpha) = cu_1 e^{-u1x} + (1\text{-}c)\, w_1 e^{-w1x} \text{ where } \alpha > 0\ u_1 > 0\ w_1 > 0, 0 \le B \le 1$$

$$s_2(\alpha) = cu_1 e^{-u2x} + (1\text{-}c)\, w_2 e^{-w2x} \text{ where } \alpha > 0\ u_2 > 0\ w_2 > 0, 0 \le B \le 1$$

$$S(\delta - \delta_1 x) = \left(\frac{u_1 c}{u_1+(\delta-\delta_1 x)}\right) + \left(\frac{w_1(1-c)}{w_1(\delta-\delta_1 x)}\right) \qquad (46)$$

$$S_2(\delta - \delta_1 x) = \left(\frac{u_2 c}{u_2+(\delta-\delta_1 x)}\right) + \left(\frac{w_2(1-c)}{w_2(\delta-\delta_1 x)}\right) \qquad (47)$$

(Hyper exponential time both for regular service and slow service, multiple vacations subject to server breakdown and repair)If the service time are assumed to be hyper exponential with probability density functions
Substituting (42) and (43) in (32) the PGF queue distribution for single server with three classes of customers subject to server breakdowns, repairs, multiple vacation can be obtained.

9. Numerical Results

The influence of various values of the server's admission probability βon the queue-length performance measures is evaluated numerically. This section presents numerical illustrations that support the theoretical findings derived earlier. To examine the impact of the positive arrival rate δ_1, the partially negative arrival rate δ_2, the negative arrival rate δ_3, as well as the expected queue length L_Q and the mean waiting time in the queue W_Q, the following notations are adopted.

Arrival rate	$\boldsymbol{\delta = \delta_1 + \delta_2 + \delta_3}$
Regular packet arrival rate	δ_1
Spoofed packet arrival rate	δ_2
Ping of death packet arrival rate	δ_3
Regular service time	μr
Slow service rate	μs
Repair time distribution is exponential with rate	ŋ1

Impact of Packet Arrival Rates on Queueing Performance Measures:

Table 1 together with Figures 2 and 3 illustrates the effect of the regular packet arrival rate $\delta_1$on the mean queue length $L_Q$and the mean waiting time W_Q. In this experiment, $\delta_1$is varied from 2 to 11, while the spoofed and ping-of-death packet arrival rates are fixed at $\delta_2 = 2.2$and $\delta_3 = 2.0$, respectively. The service rates are chosen as $\mu_r = 0.4$and $\mu_S = 0.3$, and the service-time distribution is assumed to follow Erlang-2 and hyper-exponential laws. The numerical results show that both $L_Q$and $W_Q$increase monotonically with δ_1. This behavior is due to the
increase in traffic intensity caused by higher regular packet arrivals, which leads to greater congestion and longer waiting times in the system.

The influence of the spoofed packet arrival rate δ_2 is presented in Table 2 and Figures 4 and 5. Here, δ_2 is varied from 2.2 to 4.0, while the remaining parameters are fixed at $\delta_1 = 3$, $\delta_3 = 2.0$, $\mu_r = 0.4$, and $\mu_s = 0.3$. The results indicate that both $L_Q$and W_Q initially increases as δ_2 increases, reflecting the additional load introduced by spoofed packets. However, beyond arises from the combined effects of increased spoofed traffic and the server slowdown and interruption mechanisms, which reduce the effective service capacity and temporarily lower the expected queue length and waiting time.

Table 3 together with figures 6 and 7 depicts the impact of the ping of death packet arrival rateδ_3 on the system performance measures. In this case, δ_3 is varied from 2.0 to 6.5, while the remaining parameters are fixed at $\delta_1 = 3$, $\delta_2 = 2.2$, $\mu_r = 0.4$, and $\mu_s = 0.3$.It is observed that both $L_Q$and $W_Q$gradually decrease as $\delta_3$increases. This behaviour suggests that the proposed control mechanism effectively suppresses or filters ping of death packets, thereby

preventing excessive queue accumulation and improving the overall system performance.

Table 1: Regular packet arrival δ_1 Expected queue Length LQ and Mean waiting time WQ

δ_1	Erlang -2		Hyper Exponential	
	LQ	WQ	LQ	WQ
2	0.1836	0.9274	0.1279	0.6483
3	0.3648	1.8427	0.2865	1.2386
4	0.6283	3.1179	0.4974	2.0673
5	0.9587	4.7816	0.7892	3.2461
6	1.3624	6.7945	1.1356	4.6742
7	1.8369	9.1862	1.5483	6.4187
8	2.3967	11.9735	2.0346	8.6234
9	3.0785	15.3642	2.6584	11.3189
10	3.8926	19.4875	3.4297	14.5284
11	4.8649	24.1836	4.3862	18.2473

Table 2: Spoofed packet arrival δ_2 Vs Expected queue Length LQ and Mean waiting time W_Q

δ_2	Erlang -2		Hyper Exponential	
	LQ	WQ	LQ	WQ
2.2	0.0190	0.9620	0.0140	0.6250
2.4	0.0210	1.0350	0.0145	0.6850
2.6	0.0215	1.0550	0.0148	0.7200
2.8	0.0218	1.0660	0.0150	0.7300
3.0	0.0218	1.0680	0.0153	0.7350
3.2	0.0219	1.0650	0.0153	0.7150
3.4	0.0217	1.0600	0.0152	0.7120
3.6	0.0215	1.0550	0.0151	0.7050
3.8	0.0213	1.0450	0.0150	0.7020
4.0	0.0210	1.0400	0.0148	0.7000

Table 3: Pingof death packet : δ_3 Expected queue Length LQ and Mean waiting time WQ

δ_3	Erlang -2		Hyper Exponential	
	LQ	WQ	LQ	WQ
2.0	0.0089	0.9486	0.0039	0.6754
2.5	0.0086	0.9372	0.0038	0.6681
3.0	0.0084	0.9255	0.0037	0.6593
3.5	0.0081	0.9148	0.0036	0.6527
4.0	0.0079	0.9036	0.0036	0.6451
4.5	0.0077	0.8924	0.0035	0.6392
5.0	0.0075	0.8819	0.0034	0.6338
5.5	0.0073	0.8725	0.0034	0.6294
6.0	0.0071	0.8631	0.0033	0.6242
6.5	0.0070	0.8546	0.0033	0.6201

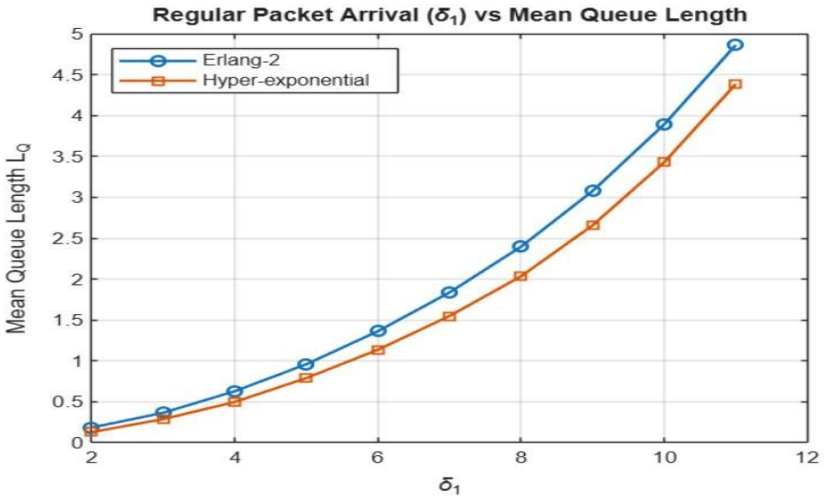


Figure 2: Regular Packet Arrival rate δ 1 (Vs) Mean Queue size LQ

Figure 3: Regular packet arrival rate **δ** 1 (Vs.) Mean Waiting Time WQ .

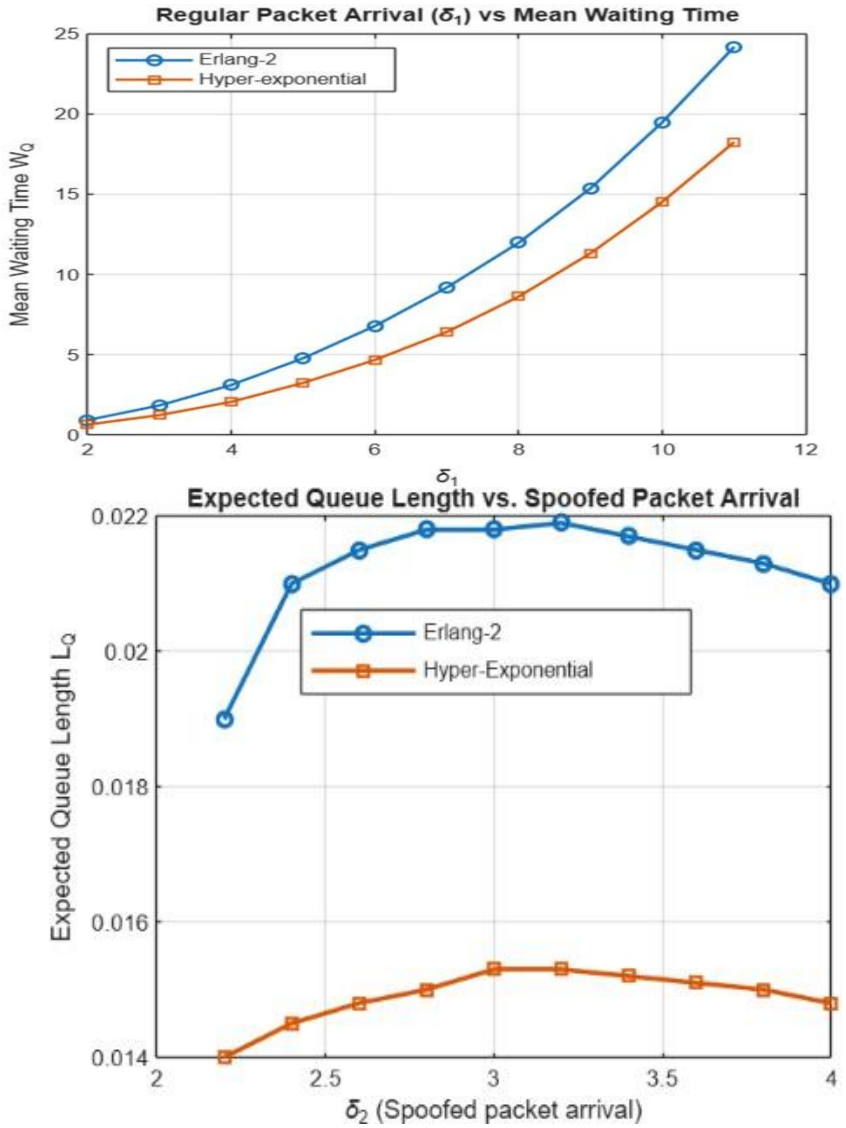
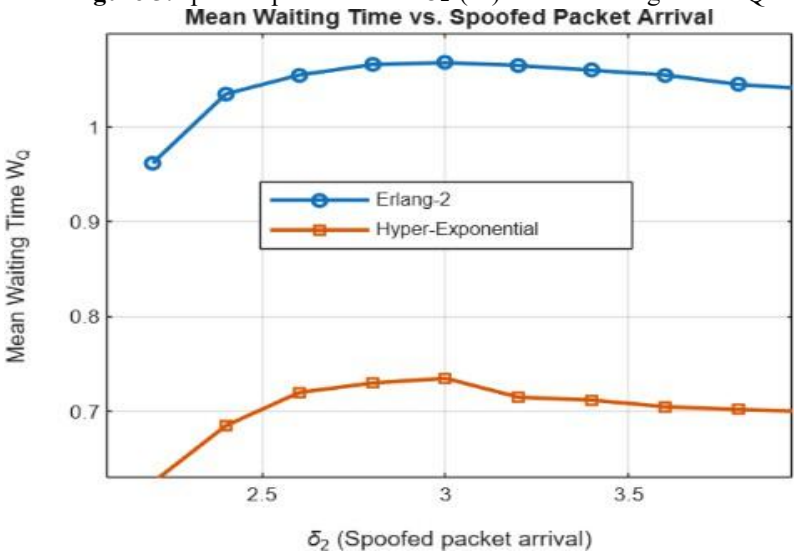


Figure 4: Spoofed packet arrival rate **δ_2** (vs) Mean Queue Length LQ .

Figure 5: spoofed packet arrival $\boldsymbol{\delta_2}$ (vs) Mean Waiting time WQ .



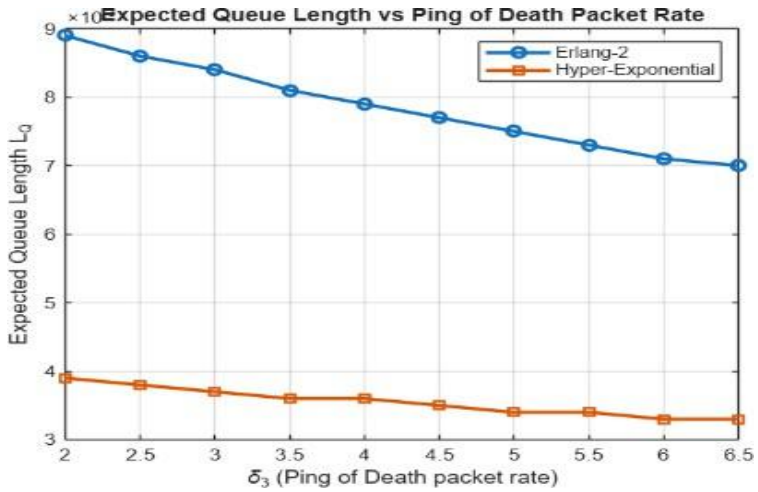


Figure 6: Ping of death packet arrival δ_3 (vs) Mean Queue Length LQ.

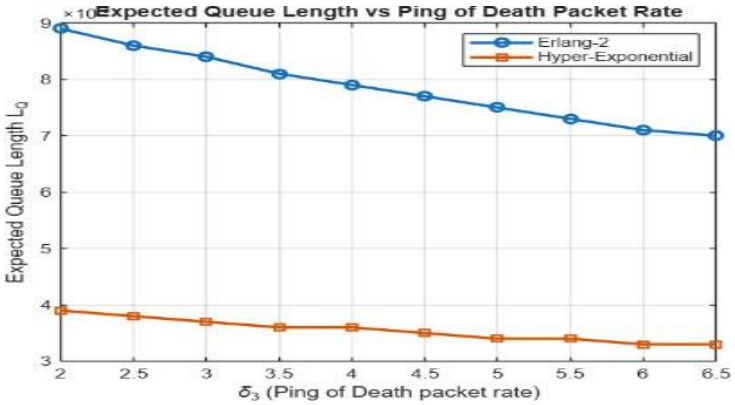


Figure 7: Ping of death packet arrival rate δ_3 (vs) Mean Waiting time WQ .

Cost Model

Cost evaluation plays a vital role in practical network management, particularly when assessing the impact of DoS attacks on system performance. In the proposed model, the average downtime cost consists of five key components: packet loss per cycle, packet holding cost, operational running cost, sleep-mode cost and repair cost. Let the following cost parameters be defined as:

C_d: packet-delay cost per cycle,

C_h: holding cost per packet per unit time,

C_o: operating cost per unit time,

C_s: sleep cost per cycle,
C_{rc}: repair cost per unit time.
Accordingly, the **total average cost (TAC)** in the proposed queueing system is given by:

$$\text{TAC} = C_s + \frac{E(v)}{P(B = 0)} + C_o E(v) + C_{rc} E(R)\ \pi_\beta.$$

This expression accounts for losses incurred due to packet drops, operational expenditure, and repair-related costs, scaled by the corresponding expected times and steady-state probabilities. The numerical example presented in this section demonstrates how network administrators in 4G/5G Core Networks (CN) can apply the performance measures developed in Sections 2.3, 2.4, and 2.6 to support informed decision-making regarding cost minimization and service reliability.
The total average costs are obtained numerically with the following assumptions:
Packet delay: Rs.13.00
Operating cost per unit time: Rs.15.00 Holding cost per customer: Rs 0.75 Operating cost per unit time: Rs. 12.00
Cost per unit time due to sleep: Rs.1.00 Repair cost per unit time: Rs.11.00
Performance Measures vs. Total average cost

Table 4: Regular packet arrival δ_1 (Vs.) Total average cost at $\beta = 0.2$, $\pi = 0.4$

$\boldsymbol{\delta_1}$	E(Q)	E(W)	E(B)	Total Average Cost
0.01	0.0038	0.3801	1.0308	10.9190
0.02	0.0109	0.0451	1.2308	10.9980
0.03	0.0414	1.3808	1.4308	10.9660
0.04	0..0991	2.4775	1.6308	10.8991
0.05	0.1652	3.304	1.8210	10.9891
0.06	0.2851	4.756	2.1310	10.9910
0.07	0.4480	6.400	2.4140	10.9110
0.08	0.6889	8.6116	2.8140	10.9901
0.09	1.0598	11.7755	3.2010	10.9910
0.10	1.5487	15.487	3.6410	10.8991

Table 5: Spoofed packet arrival δ_2 (Vs) Total Average Cost

$\boldsymbol{\delta 2}$	**E(Q)**	**E(W)**	**E(B)**	**Total Average Cost**
0.1	0.0182	0.956	0.0134	11.6210
0.2	0.0204	1.0245	0.2141	11.6810
0.3	0.0208	1.0425	0.4143	11.7161
0.4	0.0210	1.0540	0.6145	11.7261
0.5	0.0210	1.0565	0.8148	11.7311
0.6	0.0211	1.0549	1.0148	11.7111
0.7	0.0209	1.0515	1.2148	12.7111
0.8	0.0208	1.0472	1.4147	13.7011
0.9	0.0207	1.0361	1.6147	14011
1.0	0.0205	1.0315	1.8145	15.7011

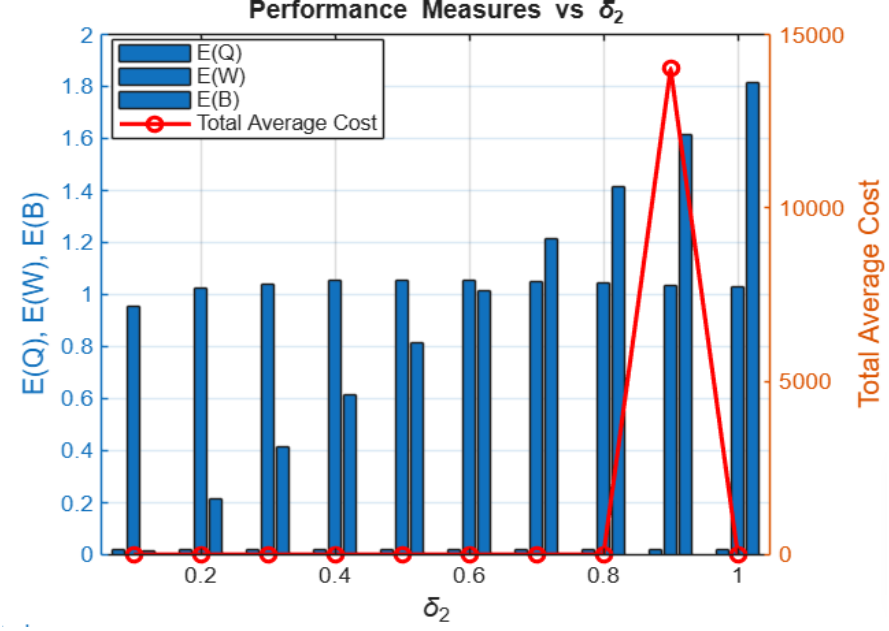


Figure 8. Spoofed packet arrival δ_2 (Vs) Total Average Cost

Table 6: Ping of death packet : δ_3 (Vs) Total average cost

δ_3	LQ	WQ	E(B)	TAC
0.1	0.0112	1.0509	0.0044	13..6177
0.2	0.0109	1.0342	0.2044	14.6170
0.3	0.0105	1.0265	0.4043	14.7254
0.4	0.0102	1.0117	0.6043	147254
0.5	0.00991	0.9887	0.8042	14.7077
0.6	0.0098	0.9875	1.0042	14.7077
0.7	0.0095	0.9777	1.2041	15.7033
0.8	0.0094	0.9691	1.4041	16.7033
0.9	0.0092	0.9614	1.6040	17.6881
1.0	0.0091	0.9598	1.8020	17.9981

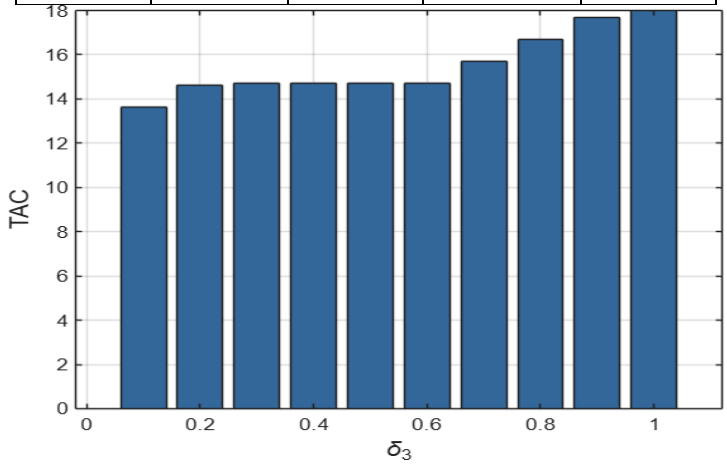


Figure 9. Ping of death packet : δ_3 (Vs) Total average cost

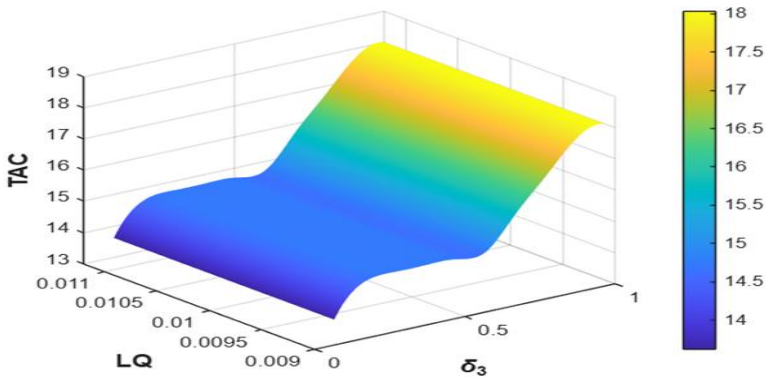


Figure 10. Ping of death packet (Vs) Mean Queue Size (Vs) Total average cost

Tables 4, 5, and 6 clearly indicate that the total operational cost rises following a denial-of-service (DoS) attack. This increase is expected, as additional expenses are incurred for mitigating the attack, restoring normal

operations, and implementing preventive measures to safeguard the system against similar future incidents**.**

Conclusion

In this paper, we have analyzed the Denial-of-Service attacks $on\ 4G/5G\ Networks$ using queuing theory approach. The arrival of packets arse classified to identify the nature of packets which are harmful to the network and reduce the performance of the networks. Addressing this suitable mathematical model is developed to predict the performance of a network by deriving the suitable performance characteristic of a network. Overall, the financial consequences of a DoS assault go beyond simple technological issues. It encompasses a range of elements related to the operations, standing, and long-term planning of an organization. Therefore, in order to lower the potential expenses related to a DoS attack, firms must implement a thorough incident response strategy and spend money on proactive cyber security solutions.

Author Contributions

S.P. Niranjan contributed to conceptualization, methodology, and supervision. K. Aswini performed formal analysis, investigation, and original draft preparation. Both authors contributed to review and editing of the manuscript.

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