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SNC BASED NETWORK LAYER DESIGN FOR UNDERWATER COMMUNICATION USED IN OPEN OCEAN FISH FARMING

T.T.Manikandan, Rajeev Sukumaran
Department of CSE
SRMIST, Chennai, Tamilnadu, India

Abstract— **Aquaculture is gradually moving toward Open Ocean Fish Farming (OOFF) in recent times because of the huge environmental impacts caused by onshore fish farming. Although Offshore fish farming has a lot of benefits over onshore fish farming it has its threats as well. Harmful Algae Blooms (HAB) are one such threat to Offshore fish farming. HAB is the formation of algae in groups that are toxic. The HAB can significantly affect the health of the fish that are being cultured. To prevent and act on HAB, monitoring of different environmental parameters is done in the field that is of concern. Traditionally for these kinds of monitoring human drivers are employed. But involving human drivers for monitoring in offshore conditions is cost expensive and difficult. Technology-enabled autonomous monitoring is needed in an offshore environment. Here comes underwater Wireless Sensor Networks (UWSN) which can be used for inspection of underwater fish farms for the detection of HAB. In UWSN loss is one of the main parameters that affect the Quality of Service. So this research focuses on the development of a Stochastic Network Calculus (SNC) based mathematical model of the network layer design for underwater communication that can be used in OOFF. In this work, we introduced the loss factor parameter into SNC and derived the loss bound for underwater communication, and the same is evaluated using discrete event simulation.**

Keywords— **SNC, Loss Factor, Loss Period, Arrival Rate, Service Rate, Buffer Size.**

I. INTRODUCTION

Fisheries have a great role to play in the food security and economic development of most developing countries. But the demand for fishes and other sea foods have continued to increase on a larger scale day by day due to the increase in population all over the world. To meet this demand many countries have concentrated on fish farming over the years which has been seen as an alternative to sea fishing. Aquaculture has contributed to about 13% of the total fish production in the world. Culturing of fish also plays a major role in reducing the attack on a variety of aquatic species in the sea by fishing activities. Fishes can more effectively convert the feed into body protein which may help in increased fish production with low expenses on feed. So Aquaculture has been considered one of the highly efficient seafood production strategies with less impact on the environment.

Coastal Fish farming is one of the most followed types of fish farming where the culturing of fish was done near the shore. Even though coastal fish farming widely practiced type of fish farming it has also imposed some negative effects on the environment. Some of them are as follows: a) the dissolved organic components and vitamins released in the process of aquaculture have a negative influence on the growth of the species. Also, there have been many situations where algae that are harmfully caused mass mortality of fully cultured fishes. b) When the cultivation of fishes is done on a larger scale it may affect the food web of other species and can lead to a reduction in minute living and non-living organisms. The only way to avoid this kind of negative impact is to move the culturing of fishes offshore. Here comes Open Ocean Fish Farming (OOFF) which is nothing but farming of marine organisms in the area which has less coastal influence with the support of systems like net pens, cages, and longline arrays. OOFF usually has very less control over the marine organisms as well as the marine environment compared to coastal aquaculture.

In OOFF, the main goal of the fish farmer is to maintain the health of the fish. So monitoring the fish farming cages and maintaining the farming environment with relatively low-stress levels and enough food for fish are of at most importance. So doing continuous monitoring in every nook of the culturing field is necessary to check if the fish farming environment is optimal for the growth of fish. Traditionally such kind of monitoring is done with the help of human drivers. But if human drivers are used for monitoring the behavior of the fishes, fishes may afraid of the human invader due to which it is impossible to monitor the fishes in their natural condition. So there needs to be an intelligent system for precise monitoring of fish in the farming field. Some of the key requirements of such an intelligent system are as follows: a) Collection of environmental parameters sensed by various sensors in the fish farming field. b) Reliable and quick transmission of sensed information such as the growth of fishes, food availability for fishes, and environmental parameters to the onshore data center for further analysis and necessary action in the aquaculture field.

II. PARAMETES TO MONITOR FOR PREVENTION OF HARMFUL ALGAE BLOOMS

One of the biggest challenges for fish farmers is monitoring and preventing algae blooms in the aqua culturing field. Phytoplankton is the smallest microscopic algae and its photosynthetic operation acts as the base for the food chain of aquatic species. But even the minimal subset of these kinds of microscopic algae can lead to the Harmful Algal Bloom (HAB). Algal blooms are not new to the aquatic ecosystem but their impacts on fish farming is rarely studied in the past. Currently due to the massive interest in open ocean fish farming the research on harmful algal blooms and their impact on the growth of fish is also gained a lot of interest.

The rapid rise of algal in the fish farming cages can result in the release of phycotoxins and de-oxygenation of water which is harmful to aquatic species. Mainly there are three categories of microorganisms available which may lead to HABs. The first category is non-toxic producing microorganisms, the second category is toxic producing microorganisms and the third category of microorganisms is non-toxic to humans but toxic to aquatic species. The non-toxic producing category of microorganisms will lead to a reduction in the dissolved oxygen quantity in the water. Also, the increase in these kinds of microorganisms may result in excessive oxygen consumption which may eventually lead to insufficient oxygen levels for the fishes being cultured and may result in the death of fishes. The category of microorganisms that are non-toxic to humans but toxic to aquatic species will affect the gills of the fish which is the vital organ that allows the fish to breathe underwater which will also lead to the death of the fish. The final and most harmful category of microorganisms is the one which are producing the toxins. This kind of microorganisms will kill the algae which is beneficial for the food chain of the aquatic species. The only way to limit the effects of harmful algae blooms in fish farming is to continuously monitor different parameters of the water in fish farming cages. Some of the parameters of the water that need to be monitored for the prevention of harmful algae blooms are discussed in the following lines.

A. Phycocyanin –

Phycocyanin is one of the most important contributors to HAB. The Phycocyanin pigment is present in all the algae and is the main source of the blue color in the blue-green algae. The levels of phycocyanin in water are one of the specific indicators of the possible occurrence of algae blooms. Phycocyanin is one of the most important parts of the biomass of cyanobacteria so monitoring its level in water where the aquatic species are being cultured can help us in finding the cyanobacteria concentration in water.

B. Temperature –

The temperature has an important role in algae growth. When there is a higher water temperature and increased light the growth rate of algae is faster. Usually, if the water temperature is in the range of 25°C then the blue-green algae which are dangerous for the aquatic species can grow at a higher rate. For most of the other types of algae, the optimal temperature for growth is in the range of 12°C to 15°C. So monitoring the water temperature continuously will help the fish farmers to take necessary precautions against the growth of HAB.

C. Nitrogen and Phosphorus –

The level of Nitrogen and Phosphorus in water can significantly contribute to the growth of HAB. The high level of these nutrients in addition to other parameters can facilitate the formation of HAB. So to control cyanobacteria formation and to detect its presence in water, continuous monitoring of nitrogen and phosphorus concentration in water is vital. The nitrogen concentration in water needs to be kept below 0.80 mg per L and phosphorous concentration below 0.05 mg per L.

Currently, fish farmers are dependent on human drivers for monitoring their fish farming fields. The deployment of human drivers in culturing far away from shore for monitoring is expensive. So the human drivers can’t provide this information to the fish farmer around the clock. But monitoring of all the above-mentioned parameters of the ocean water to effectively prevent harmful algae blooms creation is vital and needs to be done frequently. Here come the underwater sensors which can effectively do the task of collecting the samples of underwater parameters that lead to HAB and provide it to fish farmers around the clock. But the ensuring the Quality of Service in underwater sensor communication is the real challenge. So this research focuses on analytical modeling of the loss parameter in underwater communication with respect to buffer size, arrival traffic, and the service. The proposed mathematical model is also evaluated for its effectiveness using discrete event simulations.

The rset of the article is structured as follows: Section III deasls with the already existing literature with respect to math modeling of loss in the network.Followed by Section IV in which the basic notations of SNC were presented. In Seciton V the proposed Loss model for network layer of UWSN is derived using SNC. Subsequently, In section VI analysis of the obtained results were presented. Finally, Section VII concludes the article.

III. RELATED WORK

In any network Loss is a very important parameter to look after, if the Quality of Service provided by the network is concerned. In the past, based on the approximation of the probability of buffer overflow the workload loss ratio is calculated based on which the loss in the network is estimated[1-4]. But, practically this way of loss estimation have two major drawbacks. First, for some input processes, it is tough to estimate the probability of buffer overflow. Second, it is hard to quantify the relationship between the probability of buffer overflow and the loss ratio[1].

Network calculus is a mathematical theory for performance analysis of any computer network [5]. One of the extensions of network calculus is Deterministic Network Calculus (DNC)[6,7] which can be adopted for estimation of worst-case delay and backlog bound[8]. In the past, there have been some efforts to estimate the loss bound through DNC.

The new service model along with loss is proposed in [9] but due to the constrain it imposes with the usage of specific scheduling protocol its usage is limited. As per [10] the loss bound of the network can also be estimated with the help of the envelope and the moment generating function.

The authors in [11] have proposed a method for approximation of packet loss in the network using deterministic arrival and service curve. But, the performance bounds that are attained through DNC are pessimistic which is hard to attain in practical scenarios due to which the application of DNC-based loss estimation is not suitable for a highly variable network like UWSN.

To deal with the limitation of DNC, some researchers [12,13] have studied Stochastic Network Calculus(SNC) which is a probabilistic extension of DNC. To attain the stochastic QoS guarantees [14]

SNC characterizes the arrival and service process of the network based on stochastic arrival and service curves respectively. In this way, SNC becomes the most appropriate mathematical framework for modeling the UWSN which is stochastic is nature.

In this research, we assume a UWSN with a finite buffer size that is not big enough to avoid the occurrence of loss. Given the nature of the stochastic arrival and service curve, it is very difficult to estimate the number of packets dropped using the stochastic network calculation directly.

To fill this gap, we propose a novel method to calculate loss bound through SNC. To do so we introduced the loss factor parameter into SNC through which we create the loss analysis model of UWSN for the OOFF application.

The proposed model is based on the traffic amount-centric stochastic arrival curve and strict stochastic service curve which will be discussed further in the following section.

IV. BASIC NOTATIONS OF SNC

In this section, some of the basic concepts of Stochastic Network Calculus(SNC) and the notations that will be used in this article are presented.

Throughout this article notations $A_p(t)$, $S_p(t)$, and $A^*_p(t)$ are used for denoting the arrival, service, and departure processes in UWSN. Similarly, $L_p(t)$ and $B_p(t)$ will be used for representing the loss process in the time interval (0,t] and backlog in the network at time t respectively. Usually, in SNC, all the processes arriving in the network are considered nonnegative processes, and all the negative processes arriving in the network are always an increasing function. Based on the above assumptions a flow in the network is represented as follows:

$$F = \{f(.): \forall 0 \le i \le t, 0 \le f(i) \le f(t)\} \quad (1)$$

at a given time t = 0

$$A_p(0) = A^*_p(0) = S_p(0) = 0 \quad (2)$$

for any, 0≤i≤t,

$$A_p(i,t) \equiv A_p(t) - A_p(i) \quad (3)$$

$$A^*_p(i,t) \equiv A^*_p(t) - A^*_p(i) \quad (4)$$

$$S_p(i,t) \equiv S_p(t) - S_p(i) \quad (5)$$

Here the set of non-negative increasing functions is indicated by F_i . Similarly set of non-negative decreasing functions is indicated by F_d. The increasing and decreasing functions can be represented as follows,

$$\bar{F}_i = \{p(.): \forall 0 \le i \le t, 0 \le f(t) \le f(i)\} \quad (6)$$

$$\bar{F}_d = \{p(.): \forall 0 \le i \le t, 0 \le f(t) \le f(i)\} \quad (7)$$

For a functions $X_p(t)$ and $Y_p(t)$ which are non-negative in nature the following inequalities holds:

$$\sup_{0 \le i \le t} [X(i) + Y(i)] \le \sup_{0 \le i \le t} X(i) + \sup_{0 \le i \le t} Y(i) \quad (8)$$

$$\inf_{0 \le i \le t} [X(i) - Y(i)] \ge \inf_{0 \le i \le t} X(i) - \sup_{0 \le i \le t} Y(i) \quad (9)$$

Traditional algebra has two common operations namely addition and multiplication represented by + and x respectively. Similarly, SNC has min plus algebra where the addition operation in traditional algebra becomes the computation of minimum which is represented using Λ, likewise, the multiplication operation becomes addition and it is represented using +. In the case of SNC, assume there exists a set S then if there exists the element in the set which is less than or equal to all the elements set then it is called infimum which is abbreviated as inf. Similarly in a set S if there exists the least element which is greater than or equal to all the elements in the set then it is called supremum which is abbreviated as sup. The set of properties is defined for the min plus algebra as follows:

The (min, +) convolution of two functions i and j are represented as follows:

$$(i \otimes j)(z) = \inf_{0<l<k}[q] \qquad (10)$$

where,

$$q = i(l) + i(k-l) \qquad (11)$$

The (min, +) deconvolution of two functions i and j are represented as follows:

$$(i \oslash j)(z) = \sup_{t>0}\{q\} \qquad (12)$$

where,

$$q = i(z+s) = i(t) \qquad (13)$$

In SNC, the traffic model is the one that provides that abstraction of the arrival process's moment generating function. So Traffic and Server models were chosen for analytical modeling of UWSN operations play a vital role in deciding the resulting effectiveness.

In this research for deriving the analytical model for loss analysis of UWSN, we use a traffic amount-centric stochastic arrival curve as a traffic model and a stochastic strict service curve as a service model. The definitions of the chosen traffic and server models are as follows:

A. t.a.c Stochastic Arrival Curve –

$A_p \sim_{ta} \langle f,\alpha \rangle$ represents a flow in the network that follows t.a.c Stochastic Arrival Curve $\alpha \,\epsilon\, F_i$ with bounding function f $\epsilon\, F_d$; if for all $0 \le i \le t$ and for all $x \ge 0$, there holds

$$P\{A_p(i,t) - \alpha(t-i) > x\} \le f(x) \quad (14)$$

B. Stochastic Strict Service Curve –

$S_p \sim_{ssc} \langle g,\beta \rangle$ represents a network that provides strict service curve β(t) with bounding function g(x) $\epsilon\, F_d$, if during any time interval (i,t] for any $x \ge 0$ the cumulative service provided by the network satisfies

$$P\{S_p(i,t) - \beta(t-i) - x\} \le g(x) \quad (15)$$

V. SNC BASED LOSS BOUND

Most of the research concerning loss in the network is obtained approximately and it is purely based on the analysis of backlog in the network. But, in general, the approximation will always provide loose bounds [15]. With the approximation method of SNC, the buffer is assumed to have an infinite buffer size, practically which is not true. In the UWSN scenario, the backlog should never exceed the buffer size because when a packet exceeds the network buffer they are dropped. So it is very much important to estimate the loss directly instead of the backlog approximation to avoid loose bounds.

As the delay and backlog bounds are estimated in SNC based on stochastic arrival and service curves, loss in the network can not be directly estimated. The attain the loss bound in UWSN using SNC we first introduce the definition of loss period:

A. Loss Period

In a network, the loss period is the time duration that begins when the network buffer is full and the rate at which the packets arrive in the network is larger than the rate at which the packets can be serviced by the network. Such a loss period will end once the rate of arrival of a packet becomes lesser than the network service rate. Assume that (i,t] denote the loss period in the network, then during that period the amount of packet loss can be characterized as A_p(i,t) - S_p(i,t). Then the loss bound can be denoted by L_p(i,t) and can be expressed as

$$P\{L_p(i,t) > x\} = P\{A_p(i,t) - S_p(i,t) > x\}. \qquad (16)$$

Even though the definition of loss period is clear the number of such loss periods within the period of time is difficult to keep track of. Henceforth the results provided by the authors in [12] are unavoidable for our analysis and the definition of the same is illustrated below:

For any random variables A and B, and $\forall$ $x \ge 0$, if P(A > x) $\le$ f(x) and P(B > x) $\le$ g(x), where f,g $\epsilon\, F_d$, then

$$P\{A + B > x\} \le (f \otimes g)(x) \qquad (17)$$

The above results can be extended to the case of n variables. In summary, the network buffer size has a bigger impact on the resulting loss in UWSN. But in the current SNC framework, the size of the network buffer is assumed to be infinite during loss estimation and the actual impact buffer size has on the loss is not taken into the account. So, now we introduce a new parameter named loss factor into the existing SNC framework and it can be defined in the folloing subsection.

B. Loss Factor –

The loss factor is a parameter that characterizes the cumulative impact arrival, service, and network buffer size have on the loss. For a network that has a single input and output flow the loss bound can be estimated as follows:

Assume that the flow arrives at the UWSN that has a finite buffer. If the incoming flow has a t.a.c stochastic arrival cure and the network provides the flow the stochastic strict service curve there exist a z, where z>1 for $\forall$ $x \ge 0$ and $0 \le i \le t$, such that

$$P\{L_p(i,t) > x\} \leq z(f \otimes g)(x + \beta(t-i) - \alpha(t-i))$$
(18)

Note that z is determined by the network arrival rate, service the network provides and the size of network buffer bf put together. If z can be represented as a function Z(A_p(i,t),S_p(i,t),bf), then the above equation can be rewritten as follows:

$$P\{L_p(i,t) > x\} \leq Z(A_p(i,t), S_p(i,t), bf) f \otimes g(x + \beta(t-i) - \alpha(t-i))$$
(19)

When the size of network buffer denoted by bf moves towards infinity or the network service S_p(i,t) is greater than or equal to rate of arrival A_p(i,t) ∀ 0 ≤ i ≤ t and $Z(A_p$(i, t), S_p(i, t), bf) should be small enough so that it makes $Z(A_p(i,t), S_p(i,t), bf) f \otimes g(x + \beta(t-s) - \alpha(t-s))$ move towards 0.

Now we have the loss bound for single flow taking into account the arrival, service, and buffer size in the UWSN. But in a practical scenario, there will be multiple flows in the network and the loss bound estimated for a single flow needs to be extended to the multiple flows scenario as well. Unlike, DNC in SNC it is easier to transform the loss bound of a single flow to multiple flows due to the statistical multiplexing gain in SNC.

Now assume a network with a finite buffer that has N input flows with Arrival process A_p^k(t), k =1,2,...., N, respectively. Let A_p(t) represent the aggregate of arrival processes. If the network provides a stochastic strict service curve $S_p \sim_{ssc} \langle$ g,$\beta \rangle$ and ∀k, $A_p^k \sim_{ta} \langle f_k, \alpha_k \rangle$ then, if $\sum_{k=1}^{N} \alpha_k(t) < \beta(t)$ ∀ t ≥ 0,the loss bound for single flow k can be represented as follows:

$$P\{L_p^k(i,t) > x\} \leq z_k(f \otimes g)(x + \beta(t-i) - \alpha(t-i))$$
(20)

Now the loss bound for the aggregated flow in the network can be represented as follows:

$$P\{L_p(i,t) > x\} \leq z(f \otimes g)(x + \beta(t-i) - \alpha(t-i))$$
(21)

where, $f(x) = f_1 \otimes \cdots \otimes f_N(x), \alpha(t) = \sum_{k=1}^{N} \alpha_k(t)$, and z_k and z are constant value in the range of (1, +∞)

VI. RESULTS AND ANALYSIS

The evaluation of the proposed model was done using Riverbed Modeler. For the purpose of simulation, it is assumed that all the packets that are arriving into the network are of the same length. We also consider that the server follows FIFO and the time a server takes for servicing one packet is denoted by δ. It is also assumed that the arrival traffic in the network follows a Poisson process with the parameter λ.

Now for a Poisson process A_t, we have

$$P\{A_p(i+t) - A_p(i) = n\} = e^{-\lambda t} \frac{(\lambda t)^n}{n!} \qquad (22)$$

The arrival curve of the traffic in the network can be represented as follows:

$$\begin{aligned} P\{A_p(i,i+t) - \lambda t > x\} &= P\{A_p(i+t) - A(i) > \lambda t + x\} \\ &\leq \sum_{n=\lceil x+\lambda t \rceil}^{\infty} \frac{e^{-\lambda t} \cdot (\lambda t)^n}{n!} \end{aligned}$$
(23)
(23)

It is tough to estimate the bounding function with sum and the factorial so instead, we use the approximation and we arrive at the following bounding function:

$$P\{A_p(i,i+t) - \lambda t > x\} \leq e^{x - (\lambda t + x)\ln((\lambda t + x)/\lambda t)} \qquad (24)$$

Since all the packets in the network are assumed to have a fixed service time we can get the service curve as:

$$S_p(i,i+t) = ct \quad (25)$$

where f(x)=$e^{x - (\lambda t + x)\ln((\lambda t + x)/\lambda t)}$

Since the result provided by the above equation is just the CCDF of the loss and simulation provides only the number of packets that are lost in the network we use the method of approximation to get the loss factor.

For that purpose for each parameter simulation is carried out 100 times and for every l, using the below equation the loss factor z is approximated:

$$\begin{aligned} P\{L_p(t) > l\} &= zf(l + ct - \lambda t) \\ &= ze^{l + ct - \lambda t - (l + ct)\ln((l + ct)/\lambda t)} \end{aligned} \qquad (26)$$

From the analysis, it is clear that when the arrival and service curve is fixed, the smaller the loss factor it leads to tighter loss bound L_p(i,t). So when there is an increase in buffer size there is a drop in loss and that leads to a decrease in loss factor z.

Also when there is a rise in arrival rate l+ct-λt decreases and subsequently loss factor also decreases. The relationship between the loss factor and arrival curve, service curve, and buffer size are illustrated in figures 1, 2, and 3 respectively.

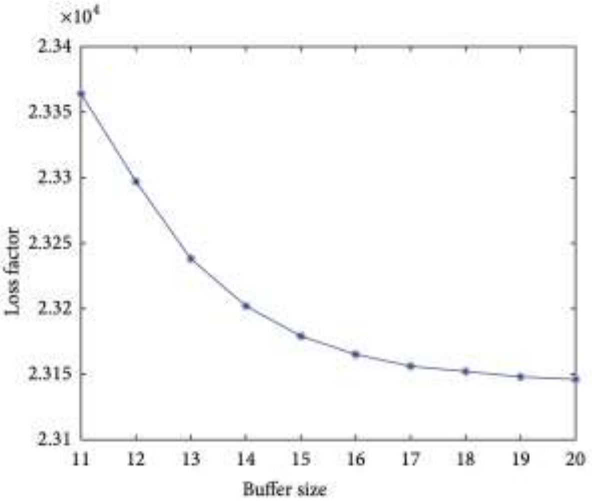

Fig. 1. Loss Factor vs Buffer Size

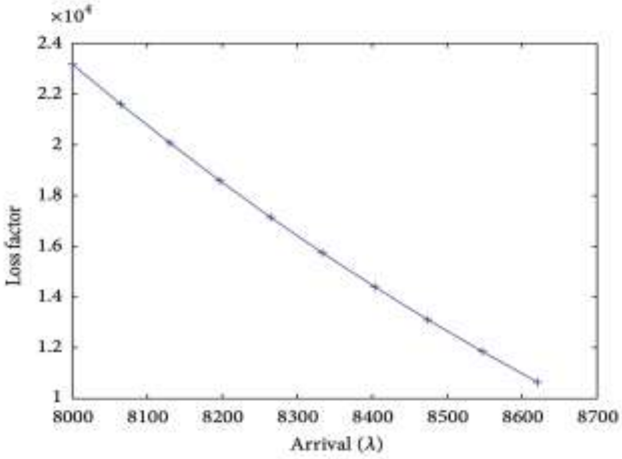

Fig. 2. Loss Factor vs Arrival Rate

From the analysis, it is clear that when the arrival and service curve is fixed, the smaller the loss factor it leads to tighter loss bound (i,t). So when there is an increase in buffer size there is a drop in loss and that leads to a decrease in loss factor z. Also when there is a rise in arrival rate l+ct- t decreases and subsequently loss factor also decreases. The relationship between the loss factor and arrival curve, service curve, and buffer size are illustrated in figures 1, 2, and 3 respectively.

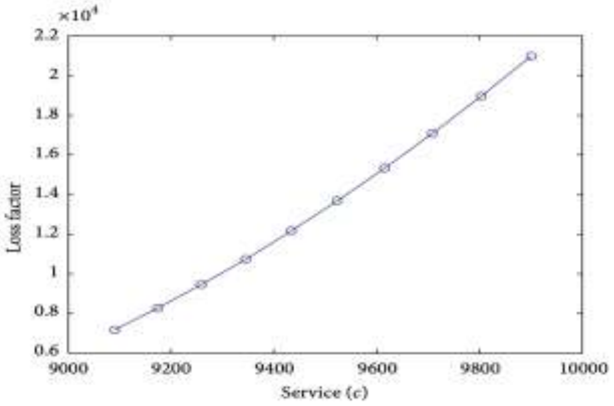

Fig. 3. Loss Factor vs Service Rate

VII.CONCLUSION

In this research, we have created an analytical model for packet loss estimation in the network layer of UWSN using stochastic network calculus for the Open Ocean Fish Farming Application. To derive the practically acceptable loss bound the new parameter named loss factor is used which takes into account the impact buffer size has on the packet loss along with the arrival and service rate in the network. The loss model derived in this research is applicable for the UWSN scenarios with multiple flows. The analytical results derived in this article are evaluated with discrete event simulations and the i) relationship between loss factor and buffer size, ii) relationship between loss factor and arrival rate, and iii) the relationship between loss factor and service are studied. But representation loss factor with the buffer size, arrival, and service curved combined is still a challenging task to establish.

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