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SNC Based Network Layer Design for Underwater Wireless Communication Used in Coral Farms

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Abstract—For maintaining the biodiversity of many ecosystems the existence of coral reefs play a vital role. But due to many factors such as pollution and coral mining, coral reefs are dying day by day. One way to protect the coral reefs is to farm them in a carefully monitored underwater environment and restore it in place of dead corals. For successful farming of corals in coral farms, different parameters of the water in the farming area need to be monitored and maintained at optimal level. Sensing underwater parameters using wireless sensor nodes is an effective way for precise and continuous monitoring in a highly dynamic environment like oceans. Here the sensed information is of varying importance and it needs to be provided with desired Quality of Service(QoS) guarantees in delivering the information to offshore monitoring centers. The main interest of this research is Stochastic Network Calculus (SNC) based modeling of network layer design for underwater wireless sensor communication. The model proposed in this research enforces differentiation of service in underwater wireless sensor communication with the help of buffer sizing and link scheduling. The delay and backlog bounds for such differentiated services are analytically derived using stochastic network calculus.

Keywords—Underwater Coral Farms, SNC, differentiated service, delay bound, backlog bound.

I. Introduction

IN oceans, the presence of corals is important for buffering the shorelines against storms, waves, and floods. In addition, corals act as the host and ensure the living of many underwater species. But over the years due to climate changes, one of the most affected ecosystems in oceans are corals. So the efforts to preserve coral reefs and their services to other underwater species are very prominent.

Climate change is one of the important factors in the destruction of coral reefs. Even at the lowest range of global warming which is less than 1.5° [1], nearly 70% to 90% of capable corals in the stage of building a reef die. Apart from this, overfishing and excess human traffic also contributes to the coral reef's stress. The increase in stress on corals not only affects the health of the coral reefs but also tends to reduce coral reef communities' natural capability to recover. When there is a reduction in the corals, it directly affects the livelihood of fishes and other underwater species which are dependent on coral. The reduction in coral reefs also weakens the lagoon's protection against surges of storms and waves.

One of the recent initiatives in preserving coral reefs is farming coral in underwater nurseries which are generally termed coral farms. In a typical coral farm, the fragments of the coral reefs are in rows. The corals which are farmed in coral farms are then migrated to the area of the ocean where the coral reefs are destroyed.

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A. Need for Real Time Monitoring of Coral Farms

For the best outcome in coral farms, different parameters of the water need to be monitored continuously and in case of change in these parameter values, necessary measures need to be taken to bring them back to optimal level in order to ensure the health and good growth rate of corals that are being farmed. Some of the parameters of water that need to be monitored in coral farms are as follows:

1) Temperature: The temperature of water in which the corals are being farmed need to be kept in the optimal range for ensuring the healthy growth of corals. The preferred range of water temperature for underwater coral farming is between 75 and 78 degrees [2]. Even though corals are more tolerable to cooler temperatures, if the water remains cold for an extended period then it may stop the growth of corals. Alternatively, when the temperature of the water becomes too hot the corals become stressed. Due to stress, the corals may expel their zooxanthellae which leads to coral bleaching. So water temperature needs to be maintained at the optimal level for effective farming of corals.

2) Calcium: If the growth of the skeletal structure of the corals is concerned, calcium in water is also an important parameter. For the development of the exoskeleton of coral reef invertebrates which is necessary for cleaning the crew of the coral reefs, presence of optimal levels of calcium in water is vital [3]. The preferred level of calcium in the water for the good growth of corals is in the range of 400-450 ppm. The growth of the corals will slow down if the calcium levels in water drop too low. Also if the calcium levels in water rise above the preferred level then it may lead to a drop in alkalinity which in turn affects the buffering capacity of the water. So frequent measurement of the calcium levels in water is vital for proper coral growth.

3) Salinity: During underwater coral farming, a certain salt-to-water ratio needs to be maintained for ensuring the survivability of corals. The required level of salinity in water for the survivability of corals is in the range of 32-35 ppt. Corals are usually very sensitive to water salinity levels. If the salinity in water goes lower than 31 ppt then it remains the same for a longer period, which may lead to the death of corals. On the other side when the salinity goes beyond 38 ppt then softer corals will begin to melt as well as the skeletons of the hard coral begin to damage [4]. Even the fluctuation in levels of salinity within the preferred range of salinity can lead to change in the color of the corals.

4) Phosphate: Phosphate is another parameter that needs to be monitored in underwater coral farms. This parameter has an impact on the color of the coral that is being farmed. The optimal range of phosphate for corals is in the range of 0.02-0.05 ppm [5]. If phosphate is not maintained at a particular level then it will lead to the development of brown algae on the top of corals which make them change their color to brown from their original bright color.

5) pH: One of the major parameters which determine the acidity of water is pH. When corals are concerned, the capability of coral to extract calcium from the water is decided by the pH concentration in the water. If the pH value in water remains too high or too low for a longer period, then it causes stress to coral and may even result in the death of the corals.

B. Differentiated Service at Network Layer for Monitoring of Underwater Coral Farm

The underwater coral farm monitoring application demands differentiated service from the network layer of the UWSN which is vital for taking necessary counter measures on time to ensure the growth of corals. When differentiated service at the network layer is concerned, many architectures are proposed in the literature, one among them is IntServ [6] which relies on link scheduling and admission control techniques to provide a wide variety of services for per-packet flow. At the granularity of different traffic categories, DiffServ [7] provides a few services by resolving scalability issues by adding a restriction to intricate techniques for internet edges. In the past, some other techniques for differentiation of services such as [8] and [9] are also proposed. Even though they are technically good, due to some legacy and economic issues they are not adopted.

The Rate Delay service architecture proposed in [10] addressed most of the above-discussed concerns by providing two categories of services such as i) Rate service which offers service at a higher rate of transmissions and ii) Delay service which offers service with low queuing delay. Among these two categories of services, no specific service is better or worst than the other, both the services are different and the effectiveness of the particular service is determined only by the specific necessity of the application. The type of service is chosen by setting a particular bit in the header of the packet that is being transmitted. The Rate Delay service architecture alters the way the packet is being forwarded but not the way routing is done. To support this differentiated service at the output link, two queues with the FIFO mechanism are maintained by the router and the service differentiation is achieved with the help of packet arrival time tracking, dynamic buffer sizing, and link scheduling. Both the category of services Rate Delay architecture offers are considered to be the best effort and it does not ensure either loss or provide guarantee to the rate. Since the architecture is simple it is adaptable in real-time.

Since Rate Delay service architecture strictly enforces constraints on queuing delay, for each packet that requires a delay category of service their arrival time needs to be monitored from time to time, this imposes additional overhead. For real-time effective service differentiation demanded by Underwater Wireless Sensor Networks (UWSN), this research proposes a service differentiation model based on Stochastic Network Calculus (SNC) which provides two categories of services namely stochastic rate service and stochastic delay service. The proposed model can accept some excessive delay which usually happens in real-time underwater acoustic communication due to environmental factors but the proposed model guarantee a low average delay. The service differentiation is accomplished by the proposed model with the help of buffer sizing and link scheduling. In this research, Stochastic Network Calculus (SNC) is adopted for the network layer modeling of UWSN which ensures stochastic service guarantees communication of underwater sensor nodes deployed for monitoring underwater coral farms. SNC is based on the min plus algebraic concept which is an alternative to regular algebra. The min plus algebra is capable of converting the network systems which are complex into entities that can be analytically tracked which is vital for the analysis of the proposed model.

The rest of the article is organized as follows: In Section II the principles and design of the proposed service differentiation model are presented. Followed by the basic notations of SNC in Section III. The network layer service differentiation model is developed by adopting relevant traffic and server models of stochastic network calculus for underwater wireless sensor communication in underwater coral farms and it is presented in Section IV. The detailed performance-bound analysis of the proposed model is presented in Section V. Finally, Section VI concludes the article.

II. Principles of Proposed Service Differentiation Model

The proposed stochastic service differentiation model offers two categories of services. The first category of service is rate service which focuses mainly on transmitting the packets having the information sensed by the underwater sensor nodes from the underwater coral farm with a higher transmission rate. The second category of service is delay service which focuses on providing the service with a lower queuing delay for the packets to be transmitted. The type of service to be offered is decided based on the sensitivity of the information and a bit in the header of the packet that is being transmitted is altered accordingly to select the particular service for the packet. For providing fair treatment of the legacy traffic they are treated under the rate category of service.

A. Processing of Arriving Packets

For providing stochastic service differentiation service for the packet arriving into the network, two FIFO queues are maintained by the router which is called as Rate queue and Delay queue respectively. All the packets that are coming into the network are distributed among both the queues based on the value of the service selection bit in the header of the packet received. The router usually keeps the link busy till the time there is a packet lined up in the transmission queue. The output capacity of the router that is in place for providing service differentiation is denoted as C. Similarly the number of flows that are traversing is denoted as N.

The number of flows from the rate and delay category of service is represented as N_{rate} and N_{delay} respectively. Both the category of queues are assumed to be in backlog condition continuously and the rate of service provided by rate and delay service queues are represented as C_{rate} and C_{delay} respectively. Based on the above definition the following conditions hold

$$N_{rate} + N_{delay} = N \tag{1}$$

and

$$C_{rate} + C_{delay} = C \tag{2}$$

B. Serving of Queues

Based on the type of queue from which the packet is being forwarded the capacity of forwarding is assigned ensuring that the ratio of r_{rate} / r_{delay} = k where k ¿ 1. Here $r_{rate}$and r_{delay} represents the forwarding rate per flow for the packets from rate and delay category respectively. By doing so the goal of differentiating the service rate of rate service and delay service is ensured by the router.

For real-time monitoring of underwater coral farms using underwater sensor networks, keeping the maximum queuing delay as lower as possible is vital. For doing so unlike the traditional Rate Delay service model the proposed model, is designed in such a way that it allows for the occasional raise in queuing delay but ensures that on average the queuing delay is maintained to the lowest value. It can be defined as follows:

$$P\{ \text{ Queuing delay of each packet being forwarded } > d\} \leq \varepsilon. \tag{3}$$

In the above equation, d represents the delay bound and the probability of the packet violating the expected performance is represented using ϵ. When the value of ϵ becomes zero then it is the special case of the stochastic service guarantee for ensuring service guarantee in the deterministic case.

C. Updation of Queuing Buffers

As illustrated earlier sizing of buffers for rate and delay queues based on requirement is another important factor through which the service differentiation is accomplished. For rate queue and delay queue, B_{rate} and B_{delay} represents their respective buffer allocations. The following bounding condition should hold for buffer allocation to the delay service queue, to ensure every packet that is being forwarded from the delay service queue does not go beyond the already defined delay bound d.

$$B_{dealy} \leq C_{delay}.d \tag{4}$$

The value of the B_{delay} should always be much lower when compared with the B which represents the overall size of the buffer available at the router. Now the allocation of buffer size for the rate service queue can be defined as:

$$B_{rate} = B - B_{delay} \tag{5}$$

The buffer size for the rate service queue is defined as larger so that available links can be utilized to the fullest by the end-to-end congestion control protocol. If there is not enough space in the buffer then the packets coming into the network are discarded by the router.

III. Basic Notations of SNC

Network calculus is the mathematical theory that can be used for performance bound estimation for the queuing system of the UWSN. Stochastic network calculus is the division of network calculus that is adopted in this research for deriving the delay and backlog bounds of the proposed service differentiation model. SNC is based on the theory of min plus algebra using which the complex network scenario can be converted into a form that can be traced analytically. Unlike Deterministic Network Calculus which doesn't take into consideration the stochastic nature of the traffic in modern-day networks like UWSN, SNC helps for utilizing the statistical multiplexing gains in a better way by taking into consideration stochastic traffic and service processes.

Throughout this research article, the arrival curve, service curve, and all the bounds are characterized as a wide sense of decreasing and non-negative functions. In a network for a single flow in the (0,t] time interval, the cumulative arrivals of the flow into the system can be represented as $A_p(t)$. Similarly, the cumulative departure of the flow from the network is represented as $A_p^*(t)$. Now the amount of service offered by the network can be denoted using $S_p(t)$. In the remaining part of this article $A_p(t)$,$S_p(t)$, and $A_p^*(t)$ are called arrival, departure, and service processes respectively with the following assumption:

$$A_p(0) = A_p^*(0) = S_p(0) = 0 \tag{6}$$

For two functions a and b its min plus convolution can be represented as follows:

$$(a \otimes b)(x) = \inf_{0<y<x} [z] \tag{7}$$

where,

$$z = a(y) + b(x - y) \tag{8}$$

Similarly, for two functions a and b its min plus deconvolution can be represented as follows:

$$(a \oslash b)(x) = \sup_{y>0} \{z\} \tag{9}$$

where,

$$z = a(x + y) - b(y) \tag{10}$$

When the performance guarantee of the UWSN is concerned two metrics that we focus on in this research are backlog and delay and they can be defined as follows: The backlog in the network at time t which is denoted using B_p(t) can be represented as follows:

$$B_p(t) = A_p(t) - A_p^*(t) \tag{11}$$

Similarly, the delay in the network at time t which is denoted using D_p(t) can be represented as follows:

$$D_p(t) = \inf \left\{ \tau \geq 0 : A_p(t) \leq A_p^*(t+\tau) \right\} \quad (12)$$

For proper characterization of incoming traffic, the traffic models that are defined in stochastic network calculus upper bounds the cumulative arrival of traffic into the network. Similarly for characterizing the service provided by the network to the incoming traffic, service models are defined in SNC, which lower bounds the cumulative service provided by the network.

Here we introduce the v.b.c stochastic arrival curve traffic model for characterizing the traffic arrivals in UWSNs and its definition is as follows:

The traffic arrival into the network denoted as $A_p(t)$ is said to follow the virtual backlog centric traffic model which can be denoted as $A_p \sim_{vb} \langle f, \alpha \rangle$ for all $y \geq 0$ and $t \geq 0$, where α represents the stochastic arrival curve with the bounding function denoted by f. Then there holds:

$$P\left\{ \sup_{0 \leq s \leq t} [A_p(s,t) - \alpha(t-s)] > y \right\} \leq f(y) \quad (13)$$

Now for the characterization of service provided by the network to the incoming traffic the stochastic service curve model is introduced and it can be defined as follows:

The service in the network denoted using $S_p(t)$ is said to follow the stochastic service curve model which is denoted using $S_p \sim_{ssc} \langle g, \beta \rangle$ for all $y \geq 0$ and $t \geq 0$, where β represents the stochastic service curve with g representing the bounding function. Then there holds:

$$P\left\{ \sup_{0 \leq s \leq t} \left[A_p \otimes \beta(t) - A_p^*(t) \right] > y \right\} \leq g(y) \quad (14)$$

When a flow in the network follows a stochastic service curve and v.b.c stochastic arrival curve then the following properties are proved [11] in SNC.

A. Delay and Backlog Bounds

When a traffic flow in the network follows $A_p \sim_{vb} \langle f, \alpha \rangle$ and $S_p \sim_{ssc} \langle g, \beta \rangle$ for all $y \geq 0$ and $t \geq 0$ the backlog in the network denoted using $B_p(t)$ is bounded by:

$$P\{B_p(t) > y\} \leq f \otimes g(y - \alpha \oslash \beta(0)) \quad (15)$$

If there are two functions p(t) and q(t) then the maximum horizontal distance between the two functions can be denoted using h(p(t),q(t)) and it cant be defined as follows:

$$h(p,q) \equiv \sup_{s \geq 0} \{\inf\{\tau \geq 0 : p(s) \leq q(s+\tau)\}\} \quad (16)$$

Now the delay in the network which is denoted as $D_p(t)$ is bounded by:

$$P\{D_p(t) > h(\alpha + y, \beta)\} \leq f \otimes g(y) \quad (17)$$

Based on the above definition, for the purpose of network performance analysis the following properties have been derived using the concept of min plus algebra:

1) Concatenation Property: Assume that the flow is traversing through the network which has two systems connected in tandem. If both the systems n=(1,2) offers a stochastic service curve $S_p^n \sim_{ssc} \langle g^n, \beta^n \rangle$ for the input then the whole flow is guaranteed to get the stochastic service curve $S_p \sim_{ssc} \langle g, \beta \rangle$ with

$$g(t) = g^1 \otimes g^2(y) \quad (18)$$

and

$$\beta(t) = \beta^1 \otimes \beta^2(t) \quad (19)$$

2) Superposition Property: Consider that there exists N flows in the network with the A_p^k(t) where k=1 to N. Then the aggregate arrival process is denoted by $A_p(t)$ and A_p^k(t) represents the independent arrival processes. If $\forall k, A_p^k \sim vb$ $\langle f_k, \alpha_k \rangle$,then $A_p \sim_{vb} \langle f, \alpha \rangle$, with,

$$f(y) = f_1 \otimes \cdots \otimes f_N(y) \quad (20)$$

and

$$\alpha(t) = \sum_{k=1}^{N} \alpha_k(t) \quad (21)$$

3) Output Property: If the input to the network follows v.b.c stochastic arrival curve $A_p \sim_{vb} \langle f, \alpha \rangle$ and the network offers the input a stochastic service curve $S_p \sim_{ssc} \langle g, \beta \rangle$ then the resulting output from the network has the virtual backlog centric stochastic arrival curve denoted by $\alpha \oslash \beta$ with $f \otimes g$ representing the bounding function, i.e

$$A_p^* \sim_{vb} \langle f \otimes g, \alpha \oslash \beta \rangle \quad (22)$$

IV. Network Layer Design for Underwater Wireless Communication in Coral Farms

For the analytical modeling of network layer operations in UWSNs, some assumptions are made. All the routers in the network offer Stochastic Rate Delay service and the links that connect the routers are assumed to have an acoustic link capacity of 10 Kbps and all the routers are assumed to have the necessary processing capacity. For our analysis, the link propagation delay is not taken into the consideration. The whole UWSN carries N_{rate}Rate and N_{delay}Delay number of flows demanding rate and delay service respectively from the sender end to the receiver end. All the acoustic access links in the network are assumed to have a capacity of 10 Kbps. With these assumptions the arrival process and service process in the network are modeled using SNC in the following subsections:

A. Modeling of Arrival Process

To characterize the real-time traffic behavior in UWSN we have introduced a generalized stochastically bounded burst (gSBB) which is a simplified version of the v.b.c stochastic arrival curve. The gSBB traffic model is symbolically denoted as $A_p \sim_{vb} \langle f, \rho t \rangle$ where f represents the bounding function and ρ represents the upper rate for all $t \geq 0$. Let,

$$Q(t;\rho) = \sup_{0 \leq s \leq t} \{z\} \quad (23)$$

where,

$$z = \{A_p(s,t) - \rho(t-s) > y\} \quad (24)$$

then there holds

$$P\{Q(t;\rho) - \rho(t-s) > \sigma\} \leq f(\sigma) \quad (25)$$

There exist many categories of traffic which belong to gSBB and almost most of those traffics have long-tailed traffic characteristics which can be modeled with the help of the power function [12].

In our case, all the flows in the network are considered to be independent of each other. In addition it is assumed that the flows that belongs to Delay Service follows v.b.c stochastic arrival curve model which is denoted as $A_p \sim_{vb} \langle f, \rho_{delay} t\rangle$ with $f(y) = ae^{-by}$. Similarly the flows belonging to rate category of service also follows v.b.c arrival curve which can be represented as $A_p \sim_{vb} \langle f, \rho_{rate} t\rangle$ with $f(y) = ae^{-by}$.

By applying the superposition property of SNC which is defined in the previous section, the aggregate of the arrival processes of the flows demanding the Delay class of service can be modeled as follows:

$$A_p^{delay} \sim_{vb} \langle f_{delay}, \alpha_{delay}\rangle \quad (26)$$

where,

$$\alpha_{delay}(t) = \sum_{k=1}^{N_{delay}} \alpha_k(t) = N_{delay}\rho_{delay} t \quad (27)$$

and

$$f_{delay}(y) = f_1 \otimes \cdots \otimes f_{N_{delay}}(y) \quad (28)$$

Similarly, the aggregate of the arrival processes of the flows demanding the Rate class of service can be modeled as follows:

$$A_p^{rate} \sim_{vb} \langle f_{rate}, \alpha_{rate}\rangle \quad (29)$$

where,

$$\alpha_{rate}(t) = \sum_{l=1}^{N_{rate}} \alpha_l(t) = N_{rate}\rho_{rate} t \quad (30)$$

and

$$f_{rate}(y) = f_1 \otimes \cdots \otimes f_{N_{rate}}(y) \quad (31)$$

B. Modeling of Service Process

To analyze the service behavior of the UWSN the router r (r= 1,2,3,4) and the server with the capacity of C^r are considered. N flows in the network shares the server based on the generalized processor sharing service technique [13]. In a network, the portion of the queue which belongs to the flow m at time t is denoted by $Q_m(t)$ and the output of that queue is denoted as $A^*_{p_m}$. Such as flow m in the network is assigned the weight which is denoted by $\phi_m > 0$. For Generalized Processor Sharing in the $(s,t]$ time interval with $Q_m(\tau) > 0$ for any $s < \tau < t$ we have:

$$\frac{A^*_{p_m}(s,t)}{A^*_{p_r}(s,t)} \geq \frac{\phi_m}{\phi_r} \quad (32)$$

As per GPS for each of the Delay and Rate class of flows the weight is assigned and it can be denoted as ϕ_{delay} and ϕ_{rate} respectively satisfying the constraint of ϕ_{rate} / ϕ_{delay} = i. For our analysis, it is assumed that $\Sigma_{m=1}^{N}\phi_m = 1$. In the time interval of $(s,t]$, for all the time if the traffic from the source m is backlogged the flow m has at least $\phi_m C^r$ service rate for the complete interval.

Since the aggregate rate of arrival for the Delay and Rate class of flows satisfies the following equation:

$$\frac{N_{rate}\rho_{rate}}{N_{delay}\rho_{delay}} = \frac{iN_{rate}}{N_{delay}} \quad (33)$$

Then the service rates available for the Rate queue and Delay queue can be represented by C^r_{rate} and C^r_{delay} and can be defined as follows respectively:

$$C^r_{rate} = \frac{N_{rate}C^r}{N_{delay} + iN_{rate}} \quad (34)$$

and

$$C^r_{delay} = \frac{N_{delay}C^r}{N_{delay} + iN_{rate}} \quad (35)$$

As per the above analysis, for the rate queue the router offers the stochastic service curve $S_p \sim_{sc} \langle g, C^r_{rate} t\rangle$ and similarly for delay queue the router offers a stochastic service curve $S_p \sim_{sc} \left\langle g, C^r_{delay} t\right\rangle$.

V. Performance Bound Analysis

Let S_p^{net} denote the service cure of the whole network, then according to the concatenation property defined in the previous section the stochastic service curve of the whole network can be represented as follows:

$$S_p^{net} \sim_{ssc} \langle g^{net}, \beta^{net}\rangle \quad (36)$$

where,

$$\beta^{net}(t) = \beta^1 \otimes \beta^2(t) \quad (37)$$

and

$$g^{net}(y) = g^1 \otimes g^2(y) \quad (38)$$

Based on the output property defined in the previous section, the flow which demands the Delay category of service from the network comes into the bottleneck link following a v.b.c stochastic arrival curve $\alpha_{delay} \oslash \beta^{net}_{delay}$ with the bounding function $f_{delay} \otimes g^{net}$ that is:

$$A^*_{delay} \sim_{vb} \left\langle f_{delay} \otimes g^{net}, \alpha_{delay} \otimes \beta^{net}_{delay}\right\rangle \quad (39)$$

Similarly, the flow demanding Rate category of service from the network comes into the bottleneck link following a v.b.c stochastic arrival curve $\alpha_{rate} \oslash \beta^{net}_{rate}$ with the bounding function $f_{rate} \otimes g^{net}$ that is:

$$A^*_{rate} \sim_{vb} \left\langle f_{rate} \otimes g^{net}, \alpha_{rate} \otimes \beta^{net}_{rate}\right\rangle \quad (40)$$

The focus of the research is on modeling the stochastic queuing delay bound of the network flows and analyzing the bottleneck link's loss rate under different conditions. The default values of different parameters considered for the model are presented in Table I.

TABLE I
DEFAULT PARAMETER SETTING CONSIDERED FOR MODELING

Parameters	Values
Total Number of Flows (N)	200
Number of Flows Demanding Delay Class of Service (N_{delay})	100
Number of Flows Demanding Rate Class of Service (N_{rate})	100
Given Delay Bound	20ms
i	3
β^2	10 Kbps
a	1
b	0.002

A. Modeling of Queue Delay Bound

Based on the definition in Section III-A the flow demanding delay class of service has the stochastic delay bound DL_d and it is bounded by:

$$P\left\{DL_{delay} > h\left(\alpha_{delay} \oslash \beta^{net}_{delay} + y, \beta^2_{delay}\right)\right\} \leq f_{delay} \otimes g^{net} \otimes g^2(y) \quad (41)$$

After some transformation we have,

$$P\left\{DL_{delay} > \frac{y}{C^2_{delay}}\right\} \leq f_1 \otimes \cdots \otimes f_{N_{delay}} \otimes g^{net} \otimes g^2(y) \quad (42)$$

By iteratively applying min plus convolution for the right side of inequality we have,

$$f_1 \otimes \cdots \otimes f_{N_{delay}} \otimes g_{net} \otimes g^2(y) = \inf_{y_1+\cdots+y_{N_{delay}+3}=y} \sum_{k=1}^{N_{delay}+3} a e^{-by_k} \quad (43)$$

Here we introduce the new definition that for any positive number of a_k and b_k where k = 1...K and y $\geq$ 0, provided $w = \sum_{k=1}^{K} \frac{1}{b_k}$ we have

$$\inf_{y_1+\cdots+y_K=y} \sum_{k=1}^{K} a_k e^{-b_k y_k} = e^{\frac{-x}{w}} \prod_{k=1}^{K} (a_k b_k w)^{\frac{1}{b_k w}} \quad (44)$$

With this, now the delay DL$_{delay}$ is bounded by:

$$P\left\{DL_{delay} > \frac{y}{C^2_{delay}}\right\} \leq e^{-\frac{yb}{N_{delay}+3}} a\left(N_{delay}+3\right) \quad (45)$$

With P_{delay} the small violation probability for delay bound, the delay bound DL$^{'}_{delay}$ can be estimated such that:

$$P\{DL_{delay} > DL^{'}_{delay}\} \leq P_{dealy} \quad (46)$$

By substituting DL$^{'}_{delay}$ = y / C^2_{delay} for the inequality at the right-hand side we can arrive at the following delay bound DL$^{'}_{delay}$:

$$DL'_{delay} = \frac{N_{delay}+3}{C^2_{delay} b} \log \frac{a\left(N_{delay}+3\right)}{P_{delay}} \quad (47)$$

Delay for the transmission of the packets can be limited to 20 ms with the violation probability of 0.8% based on the illustration presented in Fig. 1 which provides the comparison between the violation probability and the delay bound.

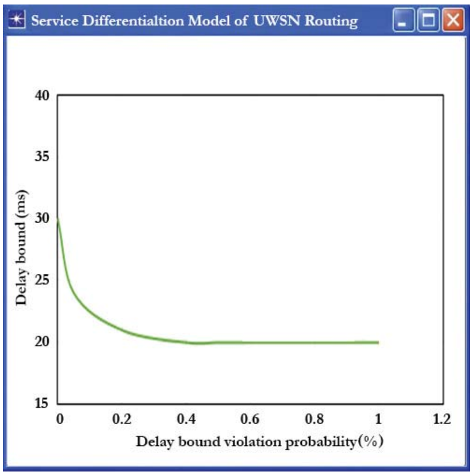

Fig. 1 Queuing delay bound vs Violation probability

B. Modeling of Loss Rate under Distinct Delay Constraints

Based on the definition in Section III-A, the stochastic backlog bound for the flow demanding delay category of service from the network can be represented as B_{delay} and it is bounded by:

$$P\left\{B_{delay} > y\right\} \leq f_{delay} \otimes g^{net} \otimes g^2\left(y - \alpha_{delay} \oslash \beta^{net}_{delay} \oslash \beta_{deay}(0)\right) \quad (48)$$

By applying the superimposition property defined in the earlier sections, we get:

$$P\left\{B_{delay} > y\right\} \leq f_1 \otimes \cdots \otimes f_{N_{delay}} \otimes g^{net} \otimes g^2(y). \quad (49)$$

Based on the definition in section III-A the backlog B_{delay} is bounded by:

$$P\left\{B_{delay} > y\right\} \leq e^{-\frac{yb}{N_{delay}+3}} a\left(N_{delay}+3\right) \quad (50)$$

Now we estimate the backlog bound $B^{'}_{delay}$ such that

$$P\{B_{delay} > B^{'}_{delay}\} \leq P_{loss} \quad (51)$$

Here P_{loss} is the probability of violation of backlog bound, y letting $B^{'}_{delay}$ = y and setting the right-hand side of the inequality to P_{loss} we can arrive at the following delay bound:

$$B'_{delay} = \frac{N_{delay}+3}{b} \log \frac{a\left(N_{delay}+3\right)}{P_{\rm loss}} \quad (52)$$

As the flows demanding delay category of service is allocated the buffer capacity of C_{delay}d the loss rate of the flows demanding delay class of service under distinct delay constraints is illustrated in Fig. 2.

From the illustration above it is clear that the loss rate of the flows demanding delay class of service tends to decrease with the increase in queuing delay bound.

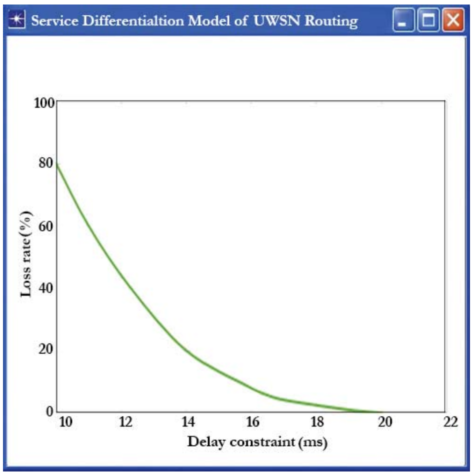

Fig. 2 Loss Rate vs Delay Constraints

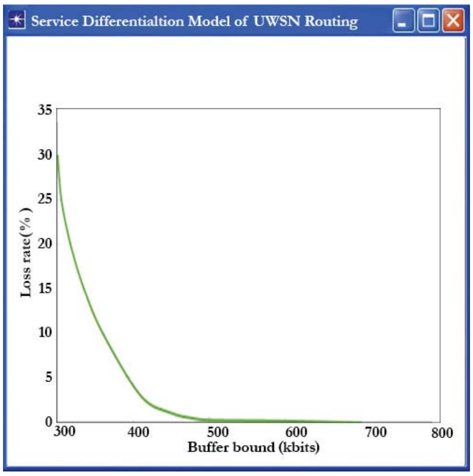

Fig. 3 Loss Rate vs Buffer Bound

C. Modeling of Loss Rate under Distinct Buffer Constraints

Similar to the definition in the previous subsection, the backlog for the flows demanding rate category of service from the network denoted by B_{rate} is bounded by:

$$P\left\{B_{rate} > y\right\} \leq e^{-\frac{yb}{N_{rate}+3}} a\left(N_{rate}+3\right) \quad (53)$$

$$P\{B_{rate} > B^{'}_{rate}\} \leq P_{loss} \quad (54)$$

Here P_{loss} is the probability of violation of backlog bound, y letting $B^{'}_{rate}$ = y and setting the right-hand side of the inequality to P_{loss} we can arrive at the following delay bound:

$$B'_{rate} = \frac{N_{rate}+3}{b} \log \frac{a\left(N_{rate}+3\right)}{P'_{\text{loss}}} \quad (55)$$

The buffer bound violation probability under distinct buffer bounds is illustrated in Fig. 3.From the illustration, it is clear that to keep the loss rate below the acceptable range the buffer capacity need to be maximized.

VI. Conclusion

As underwater wireless communication demands strict service guarantees from the underlying underwater wireless sensor network, in this research we have adopted stochastic network calculus for analyzing the provision of such service guarantees in underwater communication. The model presented in this research provides service differentiation by providing rate and delay classes of services to the network flow. This service differentiation is accomplished with the help of dynamically resizing the size of buffers and link scheduling. The proposed model endures some infrequent spike in the delay however guarantees that the flow is offered the service with an average lower delay. So the proposed model can be adopted for achieving improved network layer communication for monitoring underwater coral farms using underwater wireless sensor nodes.

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